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software defined radio

Origins, Drivers and International Perspectives

Edited by Walter Tuttlebee

Software Defined Radio

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Edited by

Walter Tuttlebee

Virtual Centre of Excellence in Mobile & Personal Communications (Mobile VCE)

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Foreword

Few people in the profession are as qualified to create a new text on software defined radio (SDR) as Walter Tuttlebee. One of the first members of the global SDR Forum, Walter was also a pioneer in military research that laid the foundations of SDR at Roke Manor. His current role, heading the Mobile Virtual Center of Excellence, keeps him in the forefront of the research and transition to practice of this eclectic collection of technologies we call software radio.

This first volume brings together a world-class collection of authors whose perspectives will help each of us deal more effectively with the proliferation of SDR applications. First, Walter differentiates the ideal or ‘pure’ software radio (my personal favorite) from the many partial instantiations of that ideal, the ‘pragmatic’ software defined radios. His review of the technology drivers and scope of SDR sets the stage. Wayne Bonser, and Allan Margulies then round out the discussion of origins and drivers. Wayne has been one of the consistent voices in the US DoD arguing the benefits of military SDR since the early 1990s. Wayne’s partnership with DARPA on the SPEAKeasy programs and their predecessors is legendary. Similarly, Allan has been one of the unsung heroes of SDR, working tirelessly in the SDR Forum as the chair (and at times the only member) of the operations committee, and now the Forum’s first employee. Alan gives a first hand perspective of the Forum as it matures into a global meeting place and melting pot for the best of the best. This section more than sets the stage, it has superb insights into the interplay of business, regulatory, and technology interests with differing perspectives around the world.

Defining the real market opportunities will remain a work in progress for some time to come. The snapshot of views in Part II can give you a starting point for your own continuing analysis. Markets change rapidly, but authors from Motorola and Morphics give you the views of a representative well-established systems supplier and a successful start-up company on this important topic. Eduardo Ballesteros and Carlos Martínez then focus specifically on third generation commercial wireless opportunities.

The interplay of markets, regulatory, and technical perspectives on SDR continues in Part III as suppliers, researchers and regulators each discuss SDR from a regional perspective. Markus Dillinger and Didier Bourse survey the European scene from a hands-on perspective in ACTS and IST. Markus, Siemens in particular and Germany overall, continues to make substantial contributions to the emergence of SDR. German contributions range from Markus’ own work to that of colleagues Jondral (U. Karlsruhe), Fettweiss (T.U. Dresden), and Werner Mohr, (Siemens), and founding chair of the Wireless World Research Forum (WWRF), just to name a few of the more famous contributors – contributions from some of these appear in Walter's next volume, *Software Defined Radio: Enabling Technologies*. Shinichiro ('Nick') Haruyama, similarly, captures the rapidly emerging Japanese program. The Japanese approach integrates the contributions of academic researchers and industrial giants in a way seldom matched around the world.

Pubudu Chandrasiri leads the transition of discussion from regional emergence to global standards. MExE was foreshadowed by the SDR Forum's groundbreaking work on secure download protocols. The MExE classmark system in some sense adapts the SDR Forum's approach to the needs of the commercial sector for simplicity and what one might call focused security (contrast with military INFOSEC). Global commercial standards supporting SDR make the regulatory tasks more manageable. Paul Bender of Germany and Stephen O'Fee of the UK then address regulatory tasks in the European Community head on, whilst Mike Grable offers an insider's view of the situation in the US. As of this writing, the US FCC had issued proposed rules intended to facilitate the reprogramming of radio functions in the field. The FCC's definition includes as an SDR any device that can change its emissions' RF frequency, bandwidth, or modulation by software. This ruling appropriately encompasses many multi-band and multi-mode wireless products in its scope.

Finally, Part IV looks at the early military and commercial markets. When I taught my first software radio course in Paris in 1996, I was most impressed with Ericsson, Nokia, and Rohde & Schwarz for the depth of understanding of these European leaders of the issues of this technology well before it emerged into the 3G migration plans several years later. I hesitate to say that the Europeans had a much better grasp of and practice with the benefits of high-end software standards and tools like Z.100, UML, and virtual machines, but they did. Few have more to offer from this head start than Ruediger Leschhorn of Rohde & Schwarz and David Hislop of RadioScape. Joined by their colleagues, these authors talk not just about the early products, but about the key abstractions – 'architectures' – that enable rapid, efficient reduction to practice. Their insights are absolutely essential for the rapid, affordable proliferation of SDR technology to military, civil, automotive, and broader commercial markets. The SDR Forum's current roadmap calls out the emergence of that cross-market synergism as a competitive advantage for the future. Those companies who best leverage that synergism should more rapidly transfer good ideas from one market segment, research group, or technology to others, reaping the benefits in market share and bottom line.

So let me conclude this foreword with enthusiastic congratulations to Walter and his world-class team for creating this timely tour de force of SDR. This text well complements other texts currently on the market. My own text, *Software Radio Architecture,* attempts to bridge the cultural divide between radio engineers and computer scientists. The IEEE text with Zoran Zvonar, *Software Radio Technologies: Selected Readings* collects those technical papers published in the IEEE until early 2001. Enrico Del Re's text *Software Radio* includes a strong collection of mostly European technical papers from his year 2000 Elba workshop. In addition, Jeff Reed (Virginia Tech, USA) and others are developing teaching texts for the English language corpus. And Walter's book – both volumes – fills a unique and critical niche in the panorama of software radio's on-going reduction to practice. Written by the world's experts, Walter included, you can't go wrong. Enjoy!

Dr. Joseph Mitola III
Consulting Scientist, MITRE Corporation

Abbreviations

2G	Second Generation Mobile Communications, e.g. GSM, TDMA
3G	3rd Generation Mobile Communications
3GPP	3rd Generation Partnership Project
A&T	Acquisition and Technology
A/D	Analogue to Digital Converter/Conversion
A2C2S	Army Aviation Command and Control System
ACTS	Advanced Communications Technologies and Services, part of the European 4th Framework Programme
ADARS	Adaptive Antenna Receive System
ADC	Analogue to Digital Converter/Conversion
ADI	Air Defense Initiative
ADM	Advanced Development Model
AFRL	Air Force Research Laboratory
AGC	Automatic Gain Control
ALC	Automatic Level Control
ALE	Automatic Link Establishment
AM	Amplitude Modulation
AMPS	American Mobile Phone System – a First Generation Analogue Mobile Phone Standard
AMTD	Affordability Manufacturability Technology Demonstration
AOC	Air Operations Center
API	Application Programming Interface
ARIB	Association of Radio Industries and Businesses, Japanese Industry Association
ARPK	Administrator Root Public Key
ARPU	Average Revenue Per User
ASIC	Application Specific Integrated Circuit
ASNR	Air Senior National Representatives
ASPEN	Advanced Signal Processing and Networking
ATC	Air Traffic Control
ATD	Advanced Technology Demonstration
ATDMA	EU supported collaborative TDMA research project under RACE
ATF	Advanced Tactical Fighter
AWE	Advanced Warfighter Experiment
BAA	Broad Area Announcement

BCS	Baseband Converter Subsystem
BCT	Brigade Combat Team
BIT	Built-In Test
BLOS	Beyond Line of Sight
Bluetooth	Short range wireless standard, intended for communication between cellphones and headsets/PCs
BMDO	Ballistic Missile Defense Organization
BRAN	Broadband Radio Access Network, an ETSI standard
BTI	Balanced Technology Initiative
C2	Command and Control
C3I	Command, Control, Communications and Intelligence
CA	Certification Authority
CAS	Close Air Support
CAST	EU supported collaborative SDR-related research project under IST
CC/PP	Composite Capability/Preference Profile
CCM	Certificate Configuration Message
CCSK	Cyclical Code Shift Keying
CDC	Control Data Corp.
CDMA	Code Division Multiple Access
CDMA-2000	3G evolution of the IS-95 digital cellular standard
CECOM	Communications & Electronics Command
CF	Core Framework
CLDC	Connected Limited Device Configuration
CLI	Common language Infrastructure
CNI	Communications, Navigation, and Identification
CNR	Combat Net Radio
CODIT	EU supported collaborative CDMA technology research projects under RACE
COMSEC	Communications Security
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off the Shelf
CP	Cryptographic Processor
cPCI	Compact PCI
CPU	Central Processing Unit
CPUAX	VHSIC Phase-II Chip
CRL	Communications Research Laboratory (Japan), also, Certificate Revocation List
CSI	Critical System Interconnect
CSP	Common Signal Processor
CTIA	Cellular Telephony Industry Association (USA)
CTR	Clock/Time/Reference
CVM®	Communication Virtual Machine
CVSD	Continuously Variable Slope Delta
CWAS	Commander's Situation Awareness Workstation
CYPRIS	Cryptographic Reduced Instruction Set [processor]
D/A	Digital to Analogue Converter/Conversion
DAB	Digital Audio Broadcasting
DAC	Digital to Analogue Converter/Conversion

DARO	Defense Airborne Reconnaissance Office
DARPA	Defense Research Projects Agency
DASD	Deputy Assistant Secretary of Defense
DCA	Defense Communications Agency
DDR&E	Director Defense Research and Engineering
DISA	Defense Information Systems Agency
DoD	Department of Defense
DRE xyz	Texas Instruments DSP DAB chip
DRiVE	EU supported collaborative SDR-related research Programme under IST
DRM	Digital Rights Management
DSP	Digital Signal Processing/Processor
DSSS	Direct Sequence Spread Spectrum
DTL	Diode-Transistor-Logic
DTMF	Dual Tone Multi Frequency
DUSD	Deputy Under Secretary of Defense
EAM	Emergency Action Message
ECCM	Electronic Counter Counter Measure
ECIT	Enhanced Communications Interface Terminal
ECM	Electronic Countermeasure
ECMA	European Computer Manufacturers' Association
EDM	Engineering Development Model
EEI	External Environment Interface
ELF	Extremely Low Frequency
ELINT	Electronic Intelligence
EMP	Electromagnetic Pulse
EPM	Electronic Protection Measures
EPROM	Erasable Programmable Read-Only Memory
ERM	Entity Reference Model
ESC	Electronic Systems Center
ESPRIT	Early European collaborative research in Information Technology
ESU	Executive Service Unit
ETSI	European Telecommunications Standards Institute
FAA	Federal Aviation Administration
FDDI	Fiber Distributed Data Interface
FDL	Fighter Data Link
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FH	Frequency Hopping
FIRST	EU supported collaborative SDR-related research Project under RACE
FM3TR	Future Multiband Multiwaveform Modular Tactical Radio
FPGA	Field Programmable Gate Array
FRAMES	EU supported collaborative research project under ACTS which played a major role in defining the 3G air interface, UTRA
FSK	Frequency Shift Keying
GBP®	Generic Baseband Processor
GloMo	Global Mobile

GPPE	General Purpose Processing Element
GPRS	Generalized Packet Radio Service, evolution of GSM
GSM	Global System for Mobile – TDMA-based Second Generation Mobile Phone Standard
GWEN	Ground-Wave Emergency Network
HaveQuick	Secure defense radio system
HF	High Frequency
HIPERLAN	ETSI wireless access/WLAN standard
HMI	Human Machine Interface
HNM	Host Network Manager
HP	Hewlett Packard
HPIB	Hewlett Packard Interface Bus
HRM	Home Reconfiguration Manager
HTTP	Hypertext Transfer Protocol
I&CP	International and Commercial Programs
I/O	Input/Output
IBMS	Integrated Broadband Mobile System, research Programme under the German national Programme
ICNIA	Integrated Communications Navigation Identification Avionics
IDL	Interface Definition Language
IEEE	Institute of Electrical and Electronics Engineers
IEICE	The Institute of Electronics, Information, and Communication Engineers, Japan
IF	Intermediate Frequency
IFF	Identification Friend or Foe
ILS	Integrated Logistics Support
IM/S	Independent Mark Space
i-Mode	Interactive cellular Internet service in Japan
IMSI	International Mobile Subscriber Identity
IMT-2000	International Mobile Telecommunications standard, 3G standards framework of the ITU
INFOSEC	Information Security
IP	Internet Protocol, also, Intellectual Property
IPT	Integrated Product Team
IrDA	Infrared data communication standard
IS-136	TDMA based 2nd Generation Digital Mobile Phone Standard
IS-95	CDMA-based 2nd Generation Digital Mobile Phone Standard
ISC	Intelligent System Controller
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ISS	Interference Suppression Subsystem
IST	Information Society Technologies, part of the European 5th Framework Programme
ISTAG	IST Advisory Group
ITU	International Telecommunications Union
J2EE	Java 2 Enterprise Edition
J2ME	Java 2 Micro Edition
J2SE	Java 2 Standard Edition
JAR	Java Archive file format

JARECO	Jam Resistant Communications
JCIT	Joint Combat Information Terminal
JCP	Java Community Process
JDL	Joint Director of Laboratories
JROC	Joint Requirements Oversight Council
JTAG	Joint Test Action Group [IEEE standard 1149.1]
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
JVM	Java Virtual Machine
JWID	Joint Warrior Interoperability Demonstration
KP	Key Processor
KVM	Kilobyte Virtual Machine
LAN	Local Area Network
LCC	Life Cycle Cost
LF	Low Frequency
LLPE	Low Latency Processing Element
LOS	Line of Sight
LPI	Low Probability of Intercept
LPI/D	Low Probability of Intercept and Detection
LRIP	Low Rate Initial Production
LRM	Line Replaceable Module
LRU	Line Replaceable Unit
LTTP	Long Term Technology Program
MAG	Market Aspects Group (of the UMTS Forum)
MATT	Multi-mission Advanced Tactical Terminal
MBMMR	Multiband Multimode Radio
MCM	Multi-Chip-Module
MEDIAN	EU supported collaborative research project under RACE
MEECN	Minimum Essential Emergency Communications Network
MEMS	MicroElectroMechanical-System
MExE	Mobile Execution Environment
MFBARS	Multifunction, Multiband, Airborne Radio System
MIDP	Mobile Information Device Profile
MIDS	Multifunction Information Distribution System
MIPS	Mega Instructions Per Second
MMAC	Multimedia Mobile Access Communication Systems
MMI	Man Machine Interface
MMITS	Modular Multifunction Information Transfer System
MNS	Mission Need Statement
MOBIVAS	EU supported collaborative SDR-related research project under IST
MONET	EU supported collaborative mobile network research project under RACE
MPHPT	Ministry of Public Management, Home Affairs, Posts and Telecommunications, Japan
MPT	Ministry of Posts and Telecommunications (Japan), now part of the MPHPT
MRPK	Manufacturer Root Public Key
MSE	MExE Service Environment
MSK	Minimal Shift Keying

NDI	Non-Developmental Item
NRaD	Naval Research and Development
NRL	Naval Research Laboratory
NSA	National Security Agency
OASD	Office of the Assistant Secretary of Defense
OCSP	Online Certificate Status Protocol
OEM	Original Equipment Manufacturer
OMG	Object Management Group
ORB	Object Request Broker
ORD	Operations Requirement Document
ORPK	Operator Root Public Key
OSD	Office of the Secretary of Defense
OSI	Open Standards Interconnect, standards body and philosophy
OS-JTF	Open System – Joint Task Force
OSP	Online Service Provider
OTA	Over The Air
P25	Standard used for North American Public Safety Communications
P3I	Pre-Planned Product Improvement
PABX	Private branch exchange – an on-site telecommunications switch
PASTORAL	EU supported collaborative SDR-related research project under IST
PCI	Personal Computer Interface
PCMCIA	Personal Computer Memory Card International Association
PDC	Personal Digital Cellular standard, Japan
PDUSD	Principal Deputy Under Secretary of Defense
PKI	Public Key Infrastructure
PKCS	Public Key Cryptographic Standard
PLMN	Public Land Mobile (telecommunications) Network
POS	Point of Sale
POSIX	Portable Operating System Interface
PPS	Preprocessor Subsystem
PRM	Proxy Reconfiguration Manager
PRN	Packet Radio Network
PROMURA	EU supported collaborative research project under RACE
PSTN	Public Service Telecommunications Network
QoS	Quality of Service
R&D	Research and Development
RACE	Research into Advanced Communications technologies in Europe, part of the European 3rd Framework Programme
RADC	Rome Air Development Center
RAP	Radio Access Point
RDEC	Research, Development and Engineering Center
RDF	Resource Description Framework
REN	Range Extension Node
RF	Radio Frequency
RFP	Request For Proposal
RNS	Residue Number System

ROM	Read Only Memory, also, Rough Order of Magnitude
RPK	Root Public Key
RRC	Rome Research Corporation
RTL	Resistor-Transistor-Logic
RTOS	Real Time Operating System
S&T	Science and Technology
SATURN	Secure defense radio system, also an EU supported collaborative SDR-related research Programme under IST
SCA	Software Communications Architecture
SCVP	Simple Certificate Verification Protocol
SDI	Strategic Defense Initiative
SDL	Specification and Definition Language
SDR	Software Defined Radio
SEM-E	Standard Electronic Module format-E
SHF	Super High Frequency
SIM	SPEAKeasy INFOSEC Module
SIM	Subscriber Identity Module
SINUS	EU supported collaborative research Programme under RACE
SIP	Silicon Intellectual Property
SLATS	EU supported collaborative research project under RACE
SLFCS	Survivable Low Frequency Communications System
SMS	Short Message Service
SoC	System on a Chip
SODERA	EU supported collaborative SDR-related research Programme under IST
SOO	Statement Of Objectives
SOPRANO	Software Programmable and Hardware Reconfigurable Architecture for Network (software radio testbed of Sony Computer Science Laboratories, Inc.)
SoRDS	Software Radio Development System (software radio testbed of AFRL)
SORT	EU supported collaborative research project under RACE
SPO	Special Program Office
SRC	Syracuse Research Corporation
SRM	Serving Reconfiguration Manager
SSL	Secure Sockets Layer
STAJ	Secure Tactical Anti-Jam
STANAG	Standard NATO Agreement
SUNBEAM	EU supported collaborative research project under RACE
SWAP	Size, Weight, and Power
SwRM	Software Reference Model
TACP	Tactical Air Control Party
TACS	Total Access Communications System (UK analogue cellular standard based on AMPS)
TADIX-B	Tactical Data Information Exchange System Broadcast
TAJPSP	Tactical Anti-Jam Programmable Signal Processor
TCDL	Tactical Common Data Link
TCS	Terminal Control System
TCTU	Tactical Communications Terminal Unit

TDMA	Time Division Multiple Access
TETRA	Trans European Trunked Radio – Digital PMR Standard
TF	Task Force
TIBS	Tactical Information Broadcast Service
TOC	Tactical Operations Center
TRANSEC	Transmission Security
TRAP	Tactical Receive Applications
TRE	Tactical Receive Equipment
TRUST	European research project IST-1999-12070 'Transparently Reconfigurable UbiquitouS Terminal'
TTCN	Tree and Tabular Combined Notation
TTP	Trusted Third Party
UCD	Use Case Diagram
UHF	Ultra High Frequency
UML	Unified Modeling Language
UMTS	Universal Mobile Telecommunications Service
U-NII	Unlicensed National Information Infrastructure
URL	Uniform Resource Locator
USAF	United States Air Force
USD	Under Secretary of Defense
USIM	Universal Subscriber Identity Module
USMC	United States Marine Corp
USN	United States Navy
UTRA	UMTS Terrestrial Air Interface
UWC-136	3G evolution of the IS-136 digital cellular standard
VAS	Value-Added Service
VCO	Voltage Controlled Oscillator
VCOS	VHSIC Chip on Silicon
VDL	VHF Digital Link
VHDL	VHSIC Hardware Description Language
VHF	Very High Frequency
VHSIC	Very High Speed Integrated Circuit
VIADAB®	Versatile Information Architecture for DAB
VLF	Very Low Frequency
VLSI	Very Large Scale Integration
VME	Versa Module EuroCard
W3C	World Wide Web Consortium
WAN	Wide Area Network
WAP	Wireless Application Protocol
WARC	World Administrative Radio Conference
WCDMA	Wideband Code Division Multiple Access
WDE	Waveform Definition Environment
WDL	Waveform Definition Language
WGS	Waveform Generator Subsystem
WINDFLEX	EU supported collaborative SDR-related research project under IST
WML	Wireless Markup Language

WNR	Wideband Network Radio
WRN	Wideband Radio Networking
WRNT	Wideband Radio Network Testbed
WSP	WAP Session Protocol
WTA	Wireless Telephone Application
XKMS	XML Key Management Specification
XML	Extensible Markup Language

Contributors' Biographies

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Walter Tuttlebee

Virtual Centre of Excellence in Mobile & Personal Communications – Mobile VCE

As Executive Director of the Virtual Centre of Excellence in Mobile & Personal Communications – Mobile VCE – Walter Tuttlebee heads up a unique non-profit company established by the mobile phone industry and academia to undertake long-term, industry-steered, collaborative research (www.mobilevce.com). Mobile VCE's activities include software radio research, an area Walter helped pioneer in Europe in the mid-1990s, whilst with Siemens Roke Manor Research, giving invited presentations at seminal European conferences, organized by the European Commission and the SDR Forum, and with subsequent IEEE publications.

Over the years Walter has led research and development teams in 2nd and 3rd generation mobile communications, as well as operating in a business development role in personal communications, digital broadcasting and satellite communications – three fields which share in common great potential for the application of software radio technologies.

Walter has edited two previous books, both on short range wireless communications, as well as conceiving and creating related on-line communities – *DECTweb* and *Bluetoothweb* (www.dectweb.org, www.bluetoothweb.org). He holds an MBA from Cranfield and PhD from Southampton University, is a Senior Member of the IEEE, a Fellow of the IEE and a Fellow of the RSA.

Contributors

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Graduated as a telecommunication engineer in 1985 from the Polytechnic University of Madrid. Eduardo Ballesteros joined Telefónica I + D in 1986 where he has held a number of positions aimed at the development of advanced networks and services. Since 1995 most of his work has been on the development of technologies and services for digital cellular networks, being lately responsible for the constitution and operation of the Mobile Multimedia Terminals Division. In the beginning of 2001 he joined Telefónica Mobile Solutions as radio manager, coordinating consulting mobile radio activities for the mobile network operators in the group. Throughout his career, he has authored a number of technical papers.

Paul Bender

RegTP

Paul Bender studied telecommunications engineering in Germany. In 1991 he joined the Bundesamt für Post und Telekommunikation (BAPT) (Federal Office for Posts and Telecommunications) in Mainz, Germany, where he was responsible for the standardization of and elaboration of type approval specifications for cordless communication systems such as DECT, CT2 and CT1+. In February 1995 he was elected Chairman of the DECT Type Approval Advisory Board (DTAAB) which was charged with the tasks of advising TRAC[1] and ACTE[2] on regulatory matters concerning DECT and elaborating proposals for submission to these committees. In 1998 the BAPT and the Ministry for Post and Telecommunications (BMPT) were merged resulting in the new Regulierungsbehörde für Telekommunikation und Post (The Regulatory Authority for Telecommunications and Posts, RegTP). In this new regulatory authority Paul Bender is responsible for the technical regulation of 3rd generation mobile systems and systems beyond.

Wayne Bonser

US Air Force Research Labs

Wayne Bonser is a principal engineer at the Air Force Research Lab in Rome, NY. He has worked in air force research and development for 29 years. He began his career working in VLF communications and was a lead engineer for technology applied to the Minimum Essential Emergency Communications Network (MEECN). He was employed as a principal scientist at the SHAPE Technical Centre, The Hague, The Netherlands from 1984 to 1989. In 1992, Mr. Bonser took the leadership role as program manager of SPEAKeasy software radio program. Mr. Bonser is currently the technical advisor to the AFRL Information Connectivity Branch, and is the focal point for AFRL's Global Grid activities.

Rainer Bott

Rohde & Schwarz GmbH

Rainer Bott received a diploma degree in electrical engineering from the Technical University of Munich in 1984. In the same year, he joined the company of Rohde & Schwarz. He held various engineering and management positions of basic research and product development.

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[1] TRAC: Technical Regulations Application Committee. Committee consisting of national administrations and network operators within the EU and EFTA.

[2] ACTE: Approvals Committee for Terminal Equipment. Committee consisting of the administrations of the EU member states. Acts as advisory committee to the European Commission on regulatory matters in the telecommunications sector.

He established key technologies in digital signal processing within the company. Now, he works in the field of digital radios and communication systems. His main interests are in digital modulation, coding and software radio technology.

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Motorola

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Dr. Gavin Ferris is CTO and co-founder of RadioScape® Ltd. At Cambridge University he was awarded the Addison Wesley prize for excellence in 1989 and graduated with first class honors the following year. He subsequently completed his PhD in the field of artificial intelligence, also at the University of Cambridge. Much of Dr. Ferris's research focused on the distributed simulation of neural networks and highly parallel real time systems. At RadioScape, Dr. Ferris pioneered the company's software defined radio architecture and used his knowledge of highly parallel, application aware, real-time systems to create the Communication Virtual Machine™ (CVM®) architecture.

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Allan Margulies

SDR Forum, USA

Allan Margulies is the chief operating officer of the Software Defined Radio Forum. He has been the secretary and chair of its Operations Committee from the beginning. He is the main contact with the Forum's membership; he supervises the office staff, office functions, and website as well as making arrangements for the meetings, and responding to member's requests.

Until recently, he was a principal communications engineer for the MITRE Corporation, a non-profit systems engineering organization, and he manages their MITRE office in Rome, NY. He has been working with software radios for the past 7 years. He has presented papers on software radio technology at the IEEE International Symposium on Spread Spectrum Techniques and Applications and at MILCOM, and he organized a session on software radios for MILCOM '99.

Allan holds a Bachelors degree in electrical engineering from New Jersey Institute of Technology and a Master's degree in electrical engineering from Northeastern University, along with a Masters degree in research and development management from American University.

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Telefónica

Born in Madrid (Spain) in 1976. Carlos Martínez graduated as a telecommunication engineer from the Polytechnic University of Madrid in 1999. After some initial research work on secondary surveillance radar systems and circular array antennas at the University, he joined Telefónica I+D in October 1999. There he worked in the field of software radio systems, attending the SDR Forum meetings and participating in a European project on reconfigurable radio (TRUST). Simultaneously he collaborated in the development of advanced mobile services. In June 2001 he moved to Telefónica Mobile Solutions, where he works as a radio consultant collaborating in the design and deployment of new Telefónica networks in Europe, America and North Africa.

Stephen O'Fee

Radiocommunications Agency, UK

Stephen O'Fee joined the UK Radiocommunications Agency in 1995 after 7 years working for the UK Ministry of Defence. Initial activities with the UK regulator involved licensing of fixed point-to-point radio communications systems. In 1998 he became involved in type approval activities and in assisting the UK's implementation of the RTTE Directive. Stephen's present role is as head of the conformity assessment activity within the Radiocommunications Agency.

John D. Ralston

StrataLight Communications

John Ralston is vice-president of Marketing at StrataLight, a company which is developing fiber transmission technology for next-generation long-haul DWDM optical networks. Previously, John served as vice-president of Marketing and vice-president of Intellectual Property and Licensing at Morphics Technology, a silicon-valley start-up developing reconfigurable signal processing solutions for 3rd generation wireless base stations and handsets, during which time John served as chairman of the SDR Forum Steering Committee. John's involvement with SDR stemmed from his earlier participation in the Sloan Business School study into the markets, commissioned by the SDR Forum, whilst completing his MSc in management of technology.

Between 1995 and 1997, whilst at SDL Inc, John led the development and commercial launch of that company's first commercial WDM fiber transmission product. Prior to this, John was responsible for establishing and managing the Optoelectronic Devices and Technologies Department at the Fraunhofer Institute for Applied Solid State Physics (Freiburg, Germany), where he led development of the world's first semiconductor lasers capable of direct modulation at 40 Gb/s and beyond. For this pioneering work, John was awarded the 1994 Prize of the German Microelectronics Society and the 1995 Young Scientist Award presented at the International Symposium on Compound Semiconductors in Seoul, South Korea. John holds BSc degrees in both physics and electrical engineering from MIT, a PhD in electrical engineering from Cornell University, and an MSc degree in the management of technology from MIT's Sloan Business School.

Introduction

Why a Series on Software Defined Radio?

Until the mid-1990s most readers would probably not have even come across the term software defined radio (SDR), let alone had an idea what it referred to. Since then SDR has made the transition from obscurity to mainstream, albeit still with many different understandings of the terms – software radio, software defined radio, software based radio, reconfigurable radio.

To a large extent this situation reflects the wide scope of both the technologies embraced and their potential implementations and applications. Thus it was, when approached to write a book for Wiley on the topic, that it was immediately apparent that a single volume would be insufficient to do the subject justice. Given this scope, and the privilege that I have had in recent years to network with many of the leading global players in the field, it seemed far more appropriate to seek specific, definitive, contributions from the experts and produce an edited authoritative work, or even a series, rather than to attempt to document a more limited personal view. These busy individuals willingly and quickly embraced the concept and agreed to participate in the project – I would like to express my personal gratitude to each one of them for this willingness, and for the timeliness and quality of their contributions, which has made this work possible.

This book serves as a broad, yet detailed, introduction to SDR, the concepts, the context, the issues, the applications, the current status and the players involved. It provides an overview of the origins of SDR, reviews some market issues, explores its global context and implications and concludes by describing a couple of early products. It represents a beginning – software radio is still in its infancy, more will follow. Notably, the companion volume *Software Defined Radio: Enabling Technologies* picks up where this book leaves off, exploring in much greater depth, the technologies which are enabling SDR.

Who is This Book For?

Over the period of my time in the communications industry my personal philosophy has evolved, and strengthened, that engineers and technologists need to appreciate the commercial context of their research and product development, whilst those engaged in the commercial functions need a fundamental grounding in the technology of their company's products. Thus, this book is intended as a training resource for those engaged in the wireless industry in both engineering and commercial roles, endeavouring, as it does, to explore the interplay between technology and commerce. It will also be valuable to engineering and business students, both graduate and undergraduate, who may be considering entering the telecommunications and IT industries. Whilst the focus is upon SDR, the underlying principles have much wider applicability – software defined systems will permeate all aspects of these industries in the coming years.

The Structure of the Book

For ease of reading, the book has been logically structured into four interconnected parts. Part I discusses origins and drivers of SDR. The first chapter seeks to provide an orientation for the reader for what follows in the remainder of the book, giving a top level introduction to origins, drivers, technology and the scope and potential impact of SDR and providing specific ‘hooks’ into subsequent chapters. Chapter 2 then provides a comprehensive description of the origins of the drivers and concepts of software radio within the US defence community, outlining the progression from the earliest ideas, through to the SPEAKeasy programme, PMCS, JTRS and more. It was these initiatives that gave birth to the MMITS Forum, now known as the SDR Forum. Chapter 3 provides a chronological description of the evolution and activities of the Forum, including its transition from a defence-driven community to its present wider commercial perspective.

Part II discusses the market opportunity and requirements of SDR. It begins with a chapter describing the MIT Sloan School of Management study of the factors influencing the development of the SDR market. This study was commissioned, and acted upon, by the SDR Forum. It offers some fascinating insights into the application of the scientific method to the understanding of technological markets, as well as providing some specific and clearly articulated strategies for industry players. Arguably the essence of market success is to achieve an optimum match of products to customers; for SDR, ‘customers’ may be considered at two levels – the end-user and the mobile network provider. Thus the next chapter describes an approach developed in Europe aimed at understanding end-user requirements of future mobile services and the implications for SDR research. The final chapter of this section explores a mobile operator perspective of the potential of SDR, within the context of third generation mobile communications and beyond, describing potential use cases, business models and changes in the industry value chain.

Part III explores the global context of SDR. The first two chapters in this section review recent research and development frameworks and activities in Europe and Japan, respectively (North America having been implicitly covered in earlier chapters). The emphases in these two regions have reflected local perspectives and specialisms. Both chapters provide comprehensive overviews and references for those wishing to pursue more detail. Standardisation is an important issue for telecommunications, especially wireless, and the next chapter explores the first embodiments of international standards as they affect SDR, in the form of the Mobile Execution Environment (MExE). MExE was standardised by the 3rd Generation Partnership Project (3GPP), but incorporated input from the SDR Forum in this process. Next to standardisation, national and regional regulation is the second issue of significance when considering SDR in a global context – to a global mobile operator, common global regulation is desirable, just as are common global standards. Thus the next two chapters explore developments on this front, firstly in Europe and then in North America.

Part IV presents descriptions of early product approaches, with just two examples, one aimed at the defence marketplace and one at the commercial one. The defence example is a military HF/VHF/UHF radio family capable of providing interoperability and flexible air interface reconfiguration. The commercial example describes an SDR-based approach to implementation of the European Digital Audio Broadcast (DAB) standard and the resulting products now on the marketplace. It concludes by describing plans to extend the approach to address the third generation mobile market.

Finally…

Whilst every effort has been made to secure a comprehensive and authoritative treatment of the subjects it is inevitable that any book of this nature will be incomplete, if only because of the fast pace of industry activity. Some of the topics treated in this book will already be familiar to some readers whilst others will be new. We have endeavoured to achieve a reasonably consistent level of treatment, although in some areas specific issues have been explored in greater depth. For those new to the field and for those wishing to probe deeper on particular topics, a selection of references has been included in each chapter, some providing general background and others addressing specific detail.

The contributors to this book, as may be seen from their biographies, are individuals who have played a significant role in the emergence of SDR and its development over recent years in North America, Europe and Asia. Their contributions reflect their own unique personal insights and perspectives – although they have all kindly adopted a common chapter structure, for the benefit of the reader. As Editor I have sought to balance the desire for readability with the desire to preserve the contributors' individual styles and opinions. This inevitably means that the views expressed in any particular chapter do not necessarily reflect those of the Editor, nor indeed those of some other contributors. The contributors, the Editor and the publishers cannot accept liability for any errors or omissions which, in any work of this nature, may occur. It would be appreciated, however, if any errors could be brought to the attention of the Editor for correction in future editions. Thank you.

Walter Tuttlebee
December 2001

Part I

Origins and Drivers

1

Setting the Scene – The What, How and Why of Software Defined Radio (SDR)[☆]

Walter Tuttlebee

Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE

Software defined radio (SDR) has emerged from obscurity to be heralded in recent years as offering a potential solution to our historical and continued inability to achieve common global mobile standards – in such a scenario reconfigurable terminals, able to adapt to the differing regional radio interfaces, appear a very attractive option. In reality, SDR offers, at the same time, both much less and much more than this. At one level, the advent of the true software reconfigurable 'universal handset' still lies in the future. Equally, however, the potential impact of software radio technologies will be profound, reaching far beyond handsets, to networks, services, applications, spectrum management and industry structures.

Software defined radio reflects the convergence of two dynamically developing technological forces of the 1990s – digital radio and software technology. The former facilitated the wireless revolution that gave birth to the mobile phone mass market whilst the latter, over the same period, has both facilitated, and ridden, the Internet wave. The massive growth and convergence of these two markets is both enabling new applications on second (2G) and third generation (3G) mobile communications networks and simultaneously changing the pre-existing ground rules of the wireless industry. Software radio is still in its infancy – in this book we explore its origins, its drivers and early activities around the globe; in the companion volume [1] we describe the enabling technologies.

In this chapter we attempt to set the scene and provide the reader with an orientation framework. We firstly explore the 'What and Why' of SDR, outlining the potential benefits of SDR, providing some terminology and asking and answering the question 'what is software defined radio?'. We then consider the 'How' – introducing at the top level the fundamental technology drivers which are enabling SDR. We then move on to explore the scope

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[☆] Portions reprinted, with permission, from "Software Defined Radio: Facets of a Developing Technology" by WHW Tuttlebee, IEEE Personal Communications, April 1999, pp. 38–44, ©1999 IEEE and potential impacts of SDR, including wider issues such as standards, regulation, spectrum management and the wider value chain impacts.

The general concepts and issues introduced in this chapter are explored in more depth in later chapters, whilst detailed implementation technology is considered in the companion volume, *Software Defined Radio: Enabling Technology* [1]. Other important sources for the serious reader include the classic 1995 Special Issue of the *IEEE Communications Magazine* [2] on the topic and Joe Mitola's book on *Software Radio Architecture* [3].

1.1 What and Why

In the final decade of the twentieth century, SDR made an incredibly rapid transition, within perhaps just 5 years, from an obscure military and academic concept to commercial credibility in the mobile phone market. In part this was due to the rapidly changing technology environment, in part due to its attraction as a potential panacea to the difficulties of securing common global standards for mobile communications and in part due to the fact that existing technologies could readily adopt the 'brand' software defined radio.

Software radio in its 'pragmatic' form – downloadable applications – is already influencing the marketplace; in its more advanced forms it will undoubtedly in due course dramatically influence the complex emerging world of twenty-first century multimedia, multimode, multiband personal communications, impacting the entire industry value chain. How will this be realized? And what are the benefits to be derived from the introduction of software radio technologies and who will derive these benefits? At the top level, examples include:

- For subscribers – easier international roaming, improved and more flexible services, increased personalization and choice.
- For mobile network operators – the potential to rapidly develop and introduce new, personalized and customized services, tools for increased customer retention, new added-value services and revenue streams, reduced costs of network evolution and enhancement, increased flexibility of spectrum management and usage.
- For handset and basestation manufacturers – the promise of new economies of scale, increased production flexibility and improved, and more rapid, product evolution.
- For regulators – the prospect of increased spectrum efficiency, better use of a scarce resource.

1.1.1 Origins

'Software radio' has emerged as an accepted term over the past few years – but one that has grown to mean different things to different people. The pace of advance in digital and software technologies will continue to accelerate, as will the proliferation of consumer wireless products, despite the market downturns of 2001. Together these factors are driving investment in 'software radio', as an enabler to reap the commercial harvest of the 3G, 'always-on-anywhere', markets. All kinds of consumer products, ranging from multimedia, Internet-capable, digital set-top boxes to personal mobile terminals, will be impacted by 'software radio' – for the reality, as noted above, is that 'software radio' is not so much a new technology, but rather a logical evolution and convergence of pre-existing digital radio and software technologies.

1.1.1.1 Digital Radio

The phenomenal growth of the digital cellular market in the 1990s was a major catalyst to investment in wireless components and digital signal processing technology. The resultant R&D allowed cost-effective, low power, implementation of previously academic, complex, algorithms. Such techniques have allowed basic limitations of earlier analog systems, such as multipath propagation, to be turned to advantage and wireless has emerged as a cost-competitive alternative to wired infrastructures for many applications, in some cases facilitating new, previously impractical, services. Digitization has now impacted virtually all commercial wireless communication and broadcast services – initially cordless and cellular telephony, followed by audio and video broadcasting (satellite, terrestrial and cable, in the form of DVB and DAB), private mobile radio (TETRA), and direct access satellite Internet, personal communications and multimedia services. The growth of the mobile phone markets in the 1990s drove the demand for ever lower power consumption, operating voltages, size and cost. Alongside this trend, and enabling it, the evolution of the PC industry similarly set the technology pace, driving reductions in silicon geometries and resulting in ever-more-powerful processing engines.

1.1.1.2 Software

The massive proliferation of computing accompanying the growth of the PC industry also spawned new applications and markets associated with the Internet, World Wide Web and Java technology, revolutionizing software products and sales channels, with the introduction of new concepts of on-line upgrade, ‘write-once, run-anywhere’, network computing and dynamic computing reconfigurability. Such trends shifted conventional boundaries, introducing new flexibility and dynamic variability in software applications operating over globally distributed networks of terminals. The emergence of World Wide Web technology has been key to commercialization, indeed consumerization, of the Internet, and is already impacting the mobile telephony industry, with mobile Intranet access seen as a key application. It was only a matter of time before these would be extended to the consumer mobile phone market.

1.1.1.3 The Genesis of Software Radio in the Defense Community

The original technical concepts of software radio however originated not in the commercial arena, but in the defense community. In the early 1990s the US Department of Defense had funded substantial defense-oriented programs, of which the best known was SPEAKeasy;[1] since that time other national programs, and indeed multinational collaborations, have been put in place. To the defense community, software radio was conceived as a way of improving interoperability whilst also reducing procurement costs, securing many of the benefits of the commercial off the shelf (COTS) approach, whilst avoiding many of the constraints. Today first products are commercially available.[2] The MMITS Forum originated from within the defense community. In the late 1990s it changed its colors, and name, today clearly targeting commercial applications under its revised name of the SDR Forum.[3]

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[1] For details, see Chapter 2.

[2] For example, the M3TR product family is described in Chapter 12.

[3] See Chapter 3.

1.1.1.4 The Transition to Commercial Credibility

The trigger for the transition for the MMITS Forum, which was accompanied by, and facilitated the credibility of software radio in the commercial wireless marketplace, was the now well-publicized request for information (RFI) from BellSouth Cellular[4] in December 1995. Since that time R&D activities have mushroomed, initially in North America but also in Europe and elsewhere. The European Commission recognized the potential importance of software radio and arranged seminal conferences with participation from the MMITS Forum,[5] although subsequently choosing to establish what it felt were important different emphases. Subsequent R&D projects under the auspices of the European Union's ACTS and IST programs focussed on concepts of 'reconfigurable radio', for 3G and beyond. Liaison between the SDR Forum and IEICE in Japan similarly stimulated research and innovation in the Asian region.[6]

1.1.2 'Pure' and 'Pragmatic' Software Radio

1.1.2.1 'Pure' Software Radio

In its original 'purist' or 'academic' form, the term software radio refers to reconfigurability of the radio interface (air interface) by software, possibly using over-the-air (OTA), download, with an often implicit assumption of A/D conversion at the antenna – see Figure 1.1. Whilst such an implementation has been feasible at very low frequency (VLF) carrier frequencies for over 20 years, such an architecture is still some way in the future for mass market personal communications products operating at 2 GHz and above. The benefits of reconfiguring a product in the field were recognized, but the wireless industry appreciated that rather than wait for technology to allow the implementation of 'pure' software radio, some of the concepts in a modified form offered earlier commercial potential.

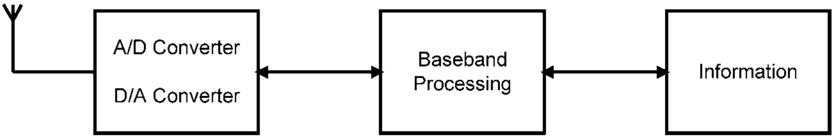

Figure 1.1 'Pure' software radio architecture

1.1.2.2 'Pragmatic' Software Radio

Thus, in the late 1990s a more pragmatic definition emerged in the personal communications arena, embracing the concept of reconfigurability at any level of the radio protocol stack, by software, either by OTA download or by other means. This represented a tacit acknowledgement that some signal processing will continue to be done in radio frequency circuitry for some years to come. This wider definition, illustrated in Figure 1.2, represents an evolutionary approach to the implementation of the concepts of software radio reconfigurability,

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[4] Written by Stephen Blust, author of the opening chapter in the companion volume to this book, *Software Defined Radio: Enabling Technology* [1].

[5] As described in Chapter 7.

[6] As described in Chapter 8.

starting at the upper layers and moving down the protocol stack as the enabling technology advances in the coming years and has become known in some circles by the more general term ‘software defined radio’. However, at the present time, ambiguities and different uses of the terminology still abound.

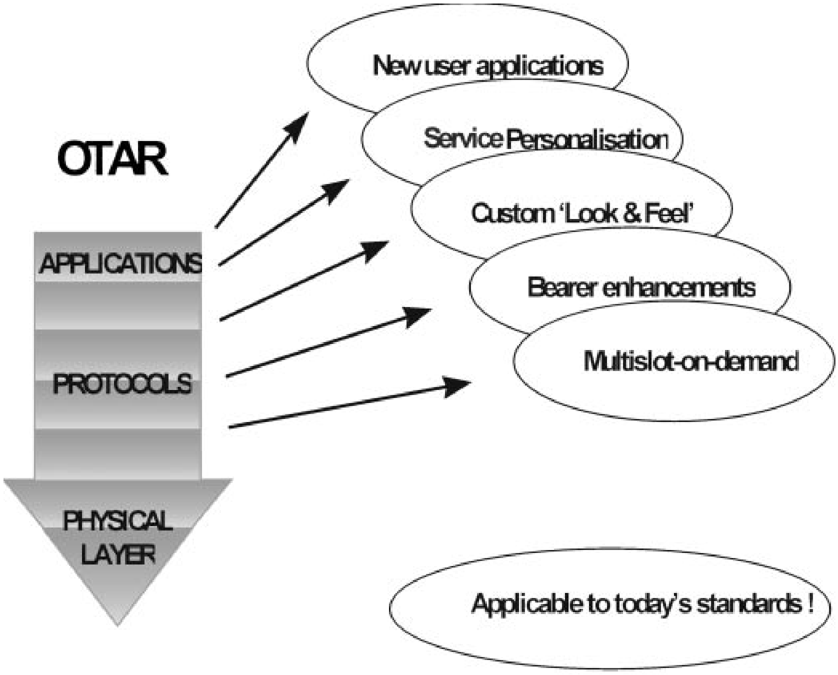

Figure 1.2 Reconfigurability can offer a range of benefits at differing levels of the protocol stack, some of which are already applicable to today’s digital standards

In Japan, dynamic application download to Java-enabled i-mode phones was introduced commercially at the start of 2001. Whilst not in the purist sense software radio, such capabilities offer operators an important means of service differentiation and new revenue streams and have thus come to set a direction for commercial development. Such download techniques can be used to provide rapid introduction of new services, flexible and interactive personalized subscriber services and operator customization of the handset interface. Moving down the protocol stack, dynamic bearer enhancements, e.g. increased bandwidth-on-demand, can be envisaged until, eventually, real time in-call air interface reconfiguration even becomes possible. At the applications layer, these concepts are clearly applicable already to 2G digital personal communications.

All of these types of reconfigurability offer highly desirable benefits to the mobile operator, who wishes to maximize customer loyalty and sell added-value services to his subscriber base. They provide ways for him to maximize the return on his investment. Within the timeframe of 3G systems – UMTS/IMT-2000 – technology will potentially permit software downloadable reconfiguration of the terminal radio interface; such radio interface reconfiguration could eventually enable important new applications.

1.1.3 SDR Markets – Geographical Differences

Considering the commercial wireless marketplace, clear differences exist between North America and Europe that have created different driving forces for software radio. These are described more fully in Ref. [4] and are summarized in Figure 1.3.

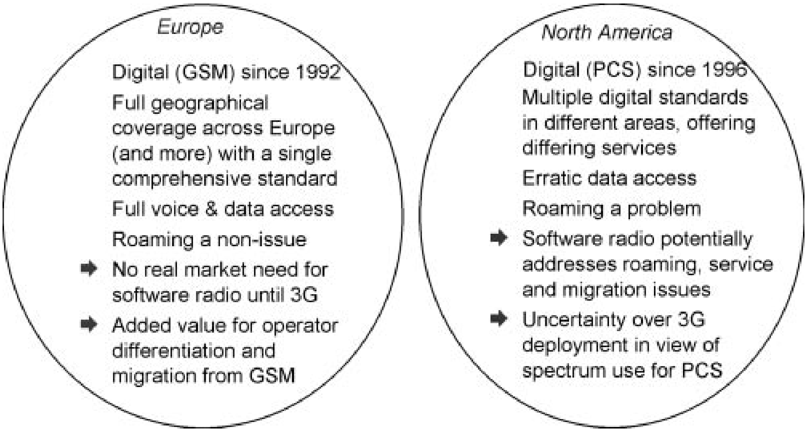

Figure 1.3 Characteristics of the European and North American markets [4]

In North America, home of the SDR Forum and of the original software radio concepts, the paucity of seamless nationwide roaming created by the existence of multiple operators and cellular standards was perceived in the mid-1990s as creating an apparent demand for multimode handsets and base stations; this view was encouraged by the BellSouth RFI. However, SDR technology could not deliver on its promise for multistandard terminals within the necessary time-scales and the subsequent consolidation of mobile operators in the US has clearly modified perceptions of this market. Indeed, early multimode software base station products in North America have met with limited market success. By contrast, in Europe the widespread availability of a single digital standard – global system for mobile communications (GSM) – has meant that 3G was perceived as the main commercial driver for new SDR-based products. Software radio base station products offer potential for network evolution from GSM to UMTS, where a requirement for backwards-compatibility exists, and where the need for dual standard handsets is anticipated. Many suppliers of innovative baseband technology for SDR have thus shifted their primary marketing focus to Europe.

1.2 How – Technology Drivers

As summarized earlier, software defined radio has been facilitated and encouraged by the evolution and convergence of digital radio and software technologies. Going down a level, the key early technologies with respect to handsets are illustrated in Figure 1.4 and summarized very briefly in this section. (Specific enabling technology is described in more detail in Ref. [1].)

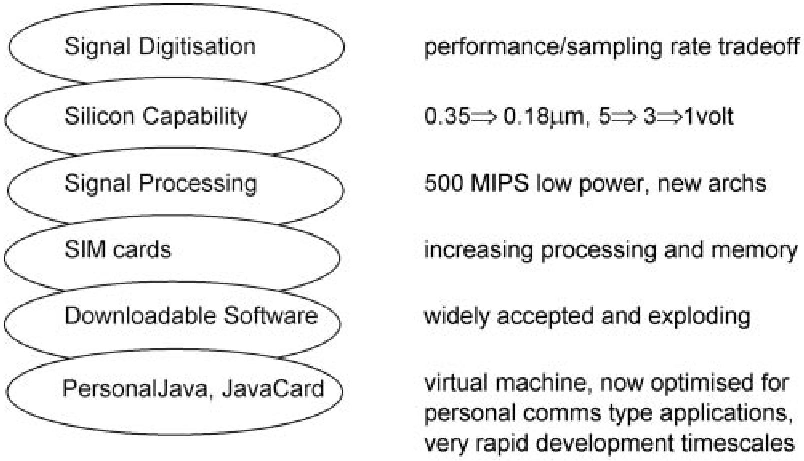

Figure 1.4 Key technology trends enabling software radio handset terminals

1.2.1 Signal Digitization

Extensive development of A/D capability in the 1990s by the semiconductor industry was stimulated by the prospects for and growth of the digital wireless markets. This resulted in dramatic improvements in accuracy, linearity, sampling rates, resolution and cost; however, the trade off between A/D performance and sampling rate continues to be a limitation. Whilst the use of multiple A/D channels may be a short-term solution, power consumption limits the application of this approach to base station products.

1.2.2 Integrated Circuit Functionality, Size and Power Consumption

Silicon geometries continue to shrink, Moore's Law has continued to be maintained, with complexities still doubling every 18–24 months. At present 0.18 µm technology is commercially available, with significant further reductions already on the way. Memory capacities continue to increase, as do the investments needed to construct their fabrication facilities! Today 3 V operation is standard in mobile phones; experimental devices have demonstrated programmable DSPs at 1 V operation, consuming a fraction of the power of the equivalent 3 V device. Such low voltage operation may need to emerge as standard in the next few years to meet the apparently insatiable demand for more processing power in portable devices.

1.2.3 DSP Processing Power

Aside from the advances in base silicon capability, advances in DSP processors have included new architectural concepts and increasingly customized hardware engines, e.g. for equalization, Viterbi processing, multi-channel demodulation and correlation; new non-Von-Neumann architectures offer increasingly power efficient implementation. Single processor DSP engines offering 200 MIPS, with power consumption around 0.5 W, were available in 1999. Since then, 3G mobile product development has served as a stimulus to accelerate such

DSP developments, as did the advent of GSM 10 years previously, with a variety of innovative technologies being introduced to the market, some of which are described in Ref. [1].

1.2.4 PersonalJava and the JavaCard

The concept of the Virtual Machine, enabling Java programs to run on any processing platform, has created the 'write-once, run-anywhere' software paradigm. Once a Java program is running, new software components can be imported and dynamically incorporated, allowing functionality enhancement on-the-fly. Java is playing a significant role in the evolution of software, not least for mobile phones as noted earlier, since the finalization of the PersonalJava[7] and JavaCard specifications.

1.2.5 Smartcard Technology

Smartcard functionality has traditionally been constrained by the size of integrated circuit that can be robustly deployed. However, as silicon geometries shrink, so the processing and memory capability within the chip footprint increases. Ratification of the JavaCard specification has enabled further flexibility enhancement of functionality for a given amount of on-card processing. Together these developments promise a rapid evolution in capability. Smartcard applications are growing fast in many markets – notably e-cash and pay-per-view conditional access to broadcast services, as well as cellphone SIM cards. The wide application domains of the technology, and resultant synergies, will have major implications for personal services of all kinds.

1.2.6 Software Download

Software sales, pricing and distribution have been revolutionized by the advent of the Internet, with its possibilities for instant impulse purchasing, easy access 'try-before-buy', and online upgrades. For the average public switched telephone network (PSTN) modem-connected PC user, downloading is still slow and frustrating and represents a bottleneck in wider acceptance at the present time. Despite such limitations, however, downloadable software over wireline is now widely and increasingly accepted – indeed upgradeable modems, using software download, are already here. Over the wireless medium, the concept is already deployed in Europe within the context of digital television.

1.3 The Scope and Impact of Software Defined Radio

1.3.1 Handset Architectures

In practice, reflecting the wide gulf between the purist view of the software radio ideal and pragmatic reality of commercially available technology today, handset manufacturers have in general chosen to adopt an understandably cautious and pragmatic approach to the imple-

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[7] PersonalJava is a specifically tuned development of Java for low memory consumer appliances, such as cellphones. For more details visit http://www.javasoft.com/products/personaljava/index.html.

mentation of software defined handsets, evolving from today's products. One example of such an approach has been described in Ref. [5].

An initial phase 1 architecture, shown in Figure 1.5, implements channel coding, source coding and control functionality in software on DSP/μC/programmable logic. This architecture is already in use for today's digital phones and allows a measure of new service introduction onto the phone in the field – in effect it allows reconfiguration at the very top of the protocol stack, the applications layer.

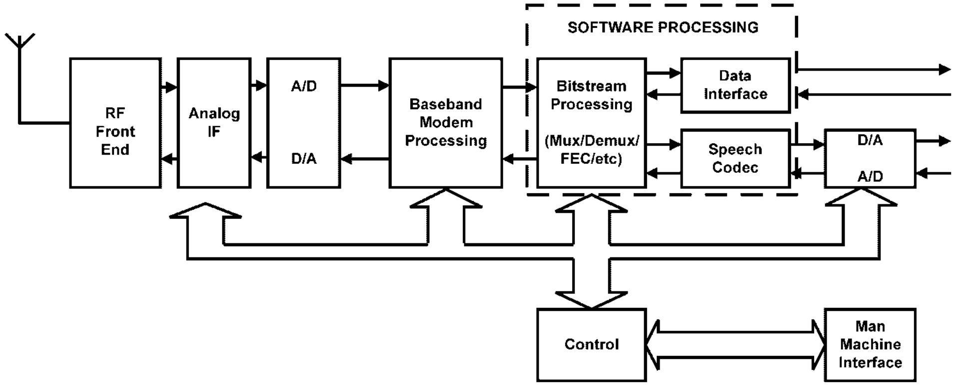

Figure 1.5 Handset evolution: phase 1

The extension of this to implement the baseband modem functionality in software is shown in Figure 1.6. This step allows the realization of new and adaptive modulation schemes under either self-adaptive or download control.

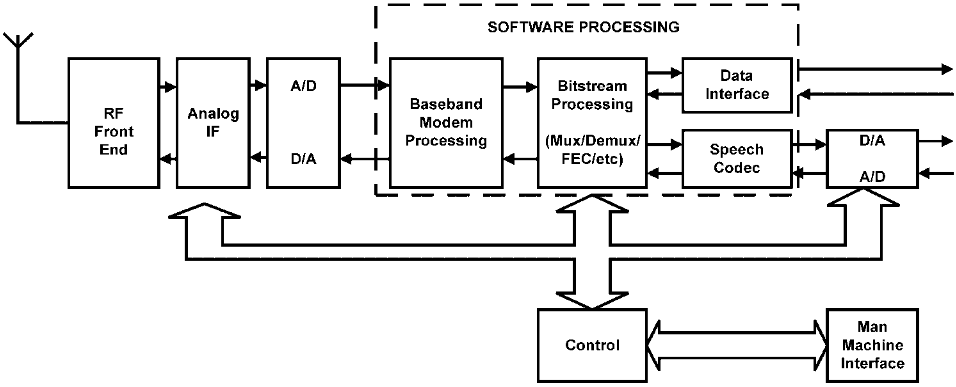

Figure 1.6 Handset evolution: phase 2

Further extension of this, involving a major change to the overall architecture to implement the IF signal processing digitally in software, will allow a single terminal to adapt to multiple radio interface standards by software reconfigurability, i.e. reconfiguration at the lowest level of the protocol stack (Figure 1.7).

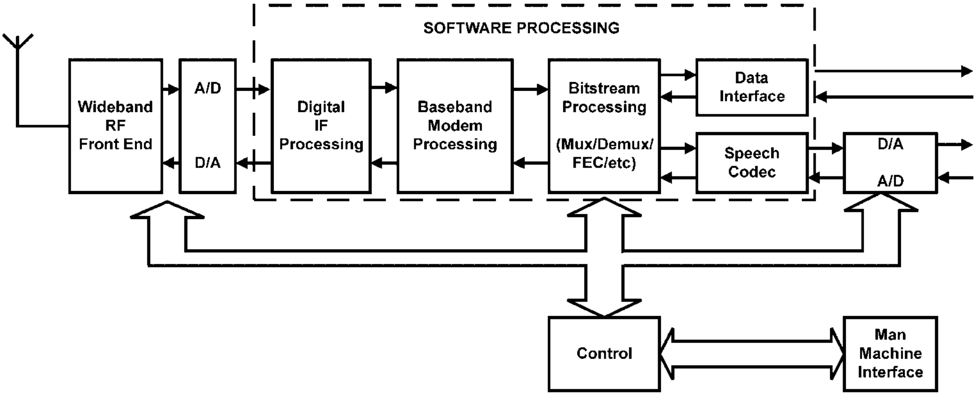

Figure 1.7 Handset evolution: phase 3

It is clear that the processing power required to implement a 'Phase 3' handset exceeds that available from generic low power DSPs in the near future by some margin. Moreover, the processing requirements of new systems – RAKE receivers, soft handover, turbo codes, etc. – would appear to be increasing faster than improvements in traditional DSP technology can deliver. This has led to the concept of augmenting generic DSP platforms with hardware specific accelerators based, as described in Refs. [4,5], to create in effect an 'SDR engine' IC. An enhancement of this concept, providing increased flexibility, is the implementation of such hardware accelerator modules using reconfigurable programmable logic. The uncertain speed at which such new concepts will progress in commercial development represents something of a wildcard when attempting to predict the pace of evolution of software handsets. Several companies are bringing such architectural implementations to market, some of which are described in Ref. [1]; however the pace of progress is likely to be influenced not simply by technology, but by the commercial success of the various companies – it is not always the best technology which achieves commercial acceptance. Such approaches illustrate the pragmatic trend towards combinations of flexible hardware/software combinations – referred to by Mitola [2] as "the use of CHFS, compatible hardware, firmware and software to achieve productisation".

1.3.2 Software Reconfiguration – Downloads and Smartcards

Software radio, at the reconfigurable air interface level, can be implemented in a handset in different ways. Three generic options exist – static, pseudo-dynamic and dynamic software download.

Static download refers to the situation where an SDR-enabled handset can support a variety of standards and is pre-programmed in a static manner to address one of these possibilities, by means of a Smartcard, for example. This represents a first step in radio interface reconfigurability.

Pseudo-static download refers to the use of OTA download to pre-configure a terminal to accommodate a defined set of applications, protocols or radio interface. Clearly this offers increased flexibility compared to the static download option, in that it puts more control into the hands of the network operator and can appear as transparent to the user.

Dynamic reconfiguration, the third option, offers yet further flexibility, allowing OTA reconfiguration to occur whilst in-call, providing, for example, bandwidth-on-demand for an advanced, time-varying, multimedia service.

These three approaches correspond, at the same time, to increasing usage flexibility and increasing implementation complexity. Possibly they may also represent evolutionary steps over the coming years.

Smartcard technology is advancing fast, as noted earlier. The step to static download by Smartcard is a small one from where we are today, allowing applications, protocol and radio interface upgrade via software downloaded to a ‘personality card’. The potential combination of today’s cellphone SIM cards with ATM/credit cards for multiple applications, is a likely scenario for the management of a wide range of personalizable services, including banking, communications and entertainment, which would support integrated payment options.

New terminals could be supplied with a mobile operator’s current local software downloaded by wire at the point-of-sale (PoS), to a Smartcard, to equip the phone with the latest release of radio interface, protocol and applications software. Some time later, as required, the user could download new facilities or services (software) onto the card from a vending machine, or even from the Internet via the user’s PC, with the cost automatically debited to the cardholder’s account. When roaming abroad, downloading a new radio interface could appear to the user as simple as buying airtime from a vending machine in an airport arrival lounge, similar to today’s rechargeable pre-paid card options.

Longer term, pseudo-dynamic OTA reconfiguration has significant logistical attractions for an operator. Over-the-air upgrade can be transparent to the user, it can allow the operator a greater degree of control and, importantly, will more readily allow new services to be sold to subscribers as ‘impulse buys’. In effect it puts the vending machine into the phone, rather than the user having to put his credit card into the vending machine, an altogether more attractive selling proposition.

Over-the-air download inherently presupposes that terminals experience neither excessive periods of continual use, nor long periods of power-down, thus missing an upgrade. A fall-back in this scenario could be to distribute an updated Smartcard to users whose terminals fail to acknowledge receipt of a software upgrade over a prolonged period.

1.3.3 Network Reconfigurability

The early focus of SDR was upon handset and base stations. However, the importance of network reconfigurability has been increasingly recognized, in large part stimulated by the activities of the European Commission IST program in this area.[8]

Just as soft handsets are envisaged as supporting multiple radio interfaces, so future mobile multimedia network infrastructures may support multiple radio interface standards. This requirement implies the need for the separation of radio-dependent and radio-independent functionality within the network. What is not yet fully clear is how an evolution from today’s 2G network infrastructures towards such concepts will be pragmatically implemented as 3G infrastructure is rolled out – clearly different vendors’ proprietary implementations will be subject to different constraints in this respect.

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[8] As described in Chapter 7.

In migrating operational networks to 3G, interworking with GSM and other pre-existing radio interfaces will be required, to provide for evolution and to allow backwards-compatibility – within Europe, networks may initially appear as 3G islands within a sea of GSM. In addition, issues of supporting home network services whilst roaming impact not only on the radio interface, which can be accommodated by OTA software download, but also upon the signaling and infrastructure support. The operational implications of the broad range of network–terminal interactions possible in a software reconfigurable network still remain to be fully understood and characterized, but is essential if the full potential of software radio is to be secured. Already, however, operators are hoping to secure reductions in infrastructure upgrade costs through such an approach; thus none of the major suppliers can afford to ignore these issues.

1.3.4 Soft Antennas and Soft Base Stations

Implementation of soft (or smart) antennas for 3G systems will not be possible using the traditional 2G approaches, with analog beamsteering at RF, but will require digital receiver architectures. Soft antennas will not be widely deployed early in the life of 3G systems, for the same reasons that we have seen with 2G – the capacity benefits are proven [6], but the cost–benefit equation does not yet square. However, the balance of cost–benefit will change and at some time in the coming years the added value of soft antennas will become positive. To accommodate an easy product evolution at that time will require the appropriate choice of base station architectures now – i.e. the use of a base station architecture that can easily evolve to accommodate adaptive digital receivers.

A basic software base station architecture is not dissimilar in concept from the handset architecture shown earlier in Figure 1.7 – the key difference, of course, is that the base station suffers from far less implementation constraints, in terms of size and power consumption, compared to a handset product. Thus such designs can be implemented already with today's technology. As implied above, in practice such software defined, multistandard, base station architectures have clear synergies with the requirements of soft antennas (and, for that matter, with a number of other advanced functions).

1.3.5 Adaptive Spectrum Management

In most countries large portions of the electromagnetic spectrum, a scarce resource, are at present permanently and inefficiently allocated to systems with low real usage. With the increasing recognition of the economic value of the radio spectrum such a situation will not in the long term be allowed to continue. Software radio technology offers one tool for harnessing this wasted resource through adaptive spectrum management (ASM).

Adaptive spectrum management, at a simple level, is already implemented in some existing wireless systems. In the DECT standard, for example, the terminal and base station both monitor their local frequency spectrum/timeslot space to identify, negotiate for and use spectrum that is currently free from interference, using Dynamic Channel Assignment [7]. In the US, the spectrum etiquette specified for the unlicensed PCS band is another example [7]. One can foresee the potential of extending such basic capabilities to negotiate dynamically not only the usage of the frequency and time space, but also to optimize the air interface to match the transmission power and modulation scheme, for example, to the required service requirements, operational range and local RF environment, as well as extending the operation of such negotiation across much wider regions of the radio spectrum. Service priority information could be included in such negotiation schemes in order to ensure that subscribers' terminals defer to those of emergency or defense services needing to use the spectrum when present. Whilst the implications of such adaptivity will pose challenges for the regulators, the economic value arguments are such that they may be forced to explore, encourage and eventually even mandate such techniques.

1.3.6 Standardization

In this new world of soft terminals and reconfigurable networks what should be standardized and how? Answers to these questions are still emerging and they are non-trivial.

To the cellular handset manufacturer involved in standards activities the radio interface has traditionally been the first aspect that springs to mind. For a soft terminal, as discussed above, it need not be necessary, beyond perhaps a basic spectral mask and other factors affecting mutual interference, to specify radio interface details. However, although not strictly necessary, a global radio interface standard to act as a bearer for local OTA software download or to provide switching instructions to handsets containing a set of preloaded options, a global beacon channel, could be desirable and has been proposed. Having said this, it could still be difficult to agree common specifications for such a global beacon channel, just as we have seen in recent years with 3G standards.

At higher levels of the protocol stack, however, if software radio is to fulfill its full potential, it is necessary to create open standards to allow different vendors' software to function on different hardware platforms, in turn connected to different networks, using different vendors' infrastructure – a non-trivial scenario, which will not be achieved overnight. Work to assess the implications of such scenarios has been undertaken within the context of the SDR Forum. The SDR Forum does not see its role as replacing that of the standardization bodies, but rather as an industry resource to create frameworks and specifications by consensus, which can then be submitted as inputs to the relevant existing bodies, in much the same way as has been done by other such fora (e.g. the ATM Forum) in recent years.

One particular area where extensive work has been undertaken by the SDR Forum is in the area of software download and the creation of an API framework for compatible software and hardware modules, which could form the basis for intra-vendor interoperability. Whilst individual companies could seek to create their own proprietary approaches, the full commercial potential of SDR is however more likely to be realized through open standards – indeed, the growth of the European wireless industry over the past decade could be said to have been based upon its wholehearted endorsement and embracing of open standards. The SDR Forum has thus contributed to the 3GPP standardization activities, in particular influencing the MexE specifications,[9] as well as providing input to the ITU process and into other organizations, to secure the role of SDR within the future mobile scenario.

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[9] See Chapter 9.

1.3.7 Regulation

Wireless product standards exist to facilitate amongst other things, conformance testing and/or type approval, important issues when one considers the potential for mutual interference from an errant soft terminal product. In Europe, the old Type Approval regime has given way to a new more flexible approach under the auspices of the so-called RTTE Directive.[10] In North America, the FCC has begun to consider the regulatory issues of SDR.[11]

Both national and international regulatory bodies will need to be educated and convinced that the evolving mechanisms for configuration management (software/hardware/network combinations) and terminal control (automatic shutdown of errantly configured equipment, for example) are both secure and reliable. In addition, issues of what degree of such external control should exist and where it should reside have yet to be determined and will not be simple to agree, since many vested interests exist – e.g. those of operators, users, national governments, civil liberties' groups, handset manufacturers and software providers amongst others. Although these issues are already being considered by the industry, firm proposals in many areas have yet to be finalized. The international dimension of securing the necessary agreements and procedures should not be underestimated. For truly dynamically reconfigurable products, at the radio interface level, to become internationally acceptable will require extensive collaboration across the global industry.

1.3.8 Service Provision – Value Chain Implications

Applications download and mobile Internet access has already begun. Whilst WAP has seen mixed success in Europe, the opposite may be said of the Japanese i-mode service, with thousands of third party providers offering new services, stimulating substantial traffic growth. The growth in provision of applications downloadable over the Internet, independent of the mobile network operators, will become unstoppable. Such growth will reflect both the pace and the trends of Internet development, such as services based on peer-to-peer architecture, enabled by third party software. Providers may be handset manufacturers, independent applications developers or today's large commercial enterprises offering new propositions targeted at their own existing, mobile-enabled, customer base.

Just as today anyone can be a web site publisher, providing limited interactive services, so in principle, in a few years time, it could be possible for almost anyone to offer new content or even services to mobile users. Mobile operators may view such developments as a threat or as an opportunity, but they cannot ignore them – their future fortunes will depend upon their response. A proactive strategy of embracing new commercial content and service partners will be key to customer retention, growth in added-value offerings and subscriber growth. Interestingly, one factor in the success of i-mode is the revenue-sharing model adopted by NTT DoCoMo, whereby the service provider receives the bulk of the subscriber revenues.

With any major technology shift comes an associated shift in power base within an industry – software radio is no exception. Many potential benefits of software radio exist at different levels of the value chain (Figure 1.8). The eventual impact will depend on how commercialization of the technologies develop. As open standards emerge, assuming that the regulatory

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[10] See Chapter 10.

[11] See Chapter 11.

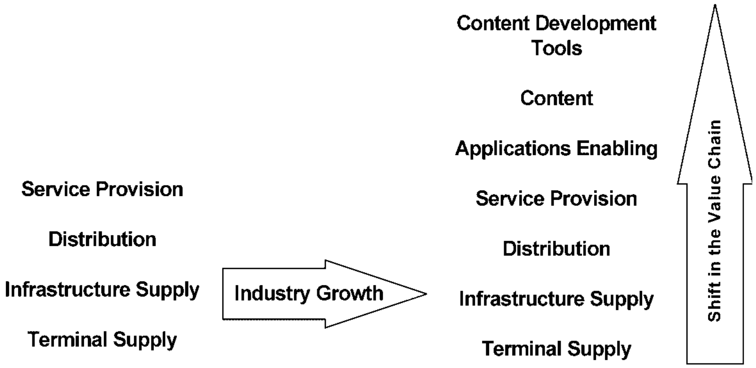

Figure 1.8 Development of the value chain For details, see the chapter by Wayne Bonser elsewhere in this volume.

issues can be adequately addressed in a timely manner, we may expect to see a new base of software providers emerging to offer not only content-based services, but enhancements in medium- and low-level handset functionality to subscribers, both directly and bundled through partner network operators.[12]

As more functionality is implemented in software a shift in end product value from hardware to software will occur – indeed this is already happening and may be expected to accelerate, generating a requirement and market for new applications enabling and content/service development tools.

1.4 Conclusions

Software radio is still today in its infancy. Already however the potential benefits, impacts and implications are beginning to be understood and recognized. Software radio cannot be ignored – players around the world are busy trying to understand its particular implications for their own position in the industry value chain. In the short term its pragmatic manifestations at the applications layer will provide network operators with some of the answers they have been seeking for customer loyalty and differentiation. In the longer term, as SDR begins to allow reconfigurability at lower levels of the protocol stack, it will have profound impacts in many different ways upon not just personal communications, but also upon other industries.

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[12] Chapter 6 addresses such opportunities and trends.

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2

US Defense Initiatives in Software Radio

Wayne Bonser

AFRL/IFGC

2.1 The Genesis of Software Defined Radio (SDR)

2.1.1 Seminal Programs and Efforts

Software defined radio (SDR), within the US military, grew out of the combination of natural technological evolution, the historical context of the era, and the resultant military strategy, which drove defense research. The introduction of technology into military hardware always lags the natural evolution of its technological research. Even though Shockley invented his junction transistor in 1948, the application of semiconductor technology did not immediately impact the communications equipment of its era. The 1950s and 1960s saw the migration from totally analog radio equipment to hybrids using transistor technology and eventually digital circuitry using resistor-transistor-logic and diode-transistor-logic. The advent of the integrated circuit in the 1960s employed transistor-transistor-logic and led to larger scale integrated circuits. In the late 1960s and 1970s the military was able to design equipment using digital technology and started to apply more complex direct sequence spread spectrum (DSSS) technology in their communications systems.

Semiconductors and digital logic enabled a revolutionary phase in the commercial market. Both the development and mass sale of portable transistor radios and the emergence of computers took place during this same era. In 1964, after 5 years of research and development, IBM introduced the first family of compatible data processing computers under the banner of their ‘IBM/360 series’. About the same time, the more scientific computers such as the CDC 6600 became available. The introduction of VLSI enabled the minicomputer revolution, with companies like HP, DEC, and Data General providing computational capability in smaller, cheaper packages that could be employed by many smaller businesses. Later, the availability of microprocessors led to the development of microcomputers built by companies like Altair, Tandy, and Commodore, and then eventually the personal computer environment we have today. The military leveraged the commercially available computer products of the time; therefore, the evolution of software radio in the military follows along a similar path.

The end of World War II, with the development and use of atomic weapons, changed forever the face of war. Thermonuclear devices soon followed and then led to multiple-warhead ballistic missiles. The availability of stockpiles of weapons of mass destruction altered military strategy. The need for a 'Balance of Power', the fear of the launch of a 'First Strike' and the ability to employ an immediate 'Massive Retaliatory Response' framed the military's strategy, and the need to survive a 'protracted nuclear war' drove its research and development.

The US military needed to provide themselves with earliest possible warnings of a 'First Strike'. They conducted surveillance and gathered intelligence on enemy weapon development, delivery, command and control, and the communication systems required. Based upon US military strategy and policy, the military needed to survive a nuclear attack, sustain operations during such an attack, reconstitute after the attack, and retaliate. For communications this meant developing technologies to survive – radiation hardening and protection against an electromagnetic pulse (EMP). It also meant hardened bunkers and buried antennas. It required communicating through a nuclear scintillated (or disturbed) ionosphere with an enhanced absorption layer. This drove the military to look to lower and lower frequency bands such as LF, VLF, and even ELF. Programs such as the minimum essential emergency communications network (MEECN) and its survivable low frequency communications system (SLFCS, operating at 14–60 kHz) component, as well as the ground-wave emergency network (GWEN, operating between 150 and 175 kHz) were established. Keen interest was shown in monitoring the deployment and operation of Soviet command and control (C2) systems and their associated communication and transmission equipment. Soviet low frequency transmissions and their associated antenna arrays became a subject of scrutiny. Countering the sophisticated warfare of a technologically advanced enemy drove US R&D towards providing robust, survivable, secure communications capable of sophisticated electronic counter-countermeasures (ECCM).

2.1.2 Early Software Controlled Digital Radio Prototypes

The availability of minicomputers and digital equipment in the early 1970s allowed development of more sophisticated surveillance equipment. Software 'controlled' digital radios enabled greater flexibility and automated control of suites of communications equipment for both electronic intelligence (ELINT) and potential electronic countermeasures (ECM). AF invention #11,142, filed by the Air Force's Rome Air Development Center (RADC), was one such implementation. The effort began in the summer of 1973 and culminated in a patent application in December 1974. This invention was the integration of an ASR-33 teletypewriter, a Data General Nova 1200 minicomputer, with Hewlett Packard digitally controlled network analysis and frequency synthesis equipment in order to create a programmable (in Fortran) computer controlled VLF ELINT receiver (see Figure 2.1). The VLF receive terminal employed the HP interface bus (HPIB) to interconnect the Nova with the HP equipment. The HPIB was eventually adopted by the IEEE and made into a standard (IEEE-488) in the late 1970s.

Buried antenna arrays were also important research topics and various types were exam-

Figure 2.1 One of the earliest software controlled receivers, operated at VLF

ined for employment at strategic communications sites. Transportable VLF receive-antenna arrays were developed in the late 1970s. The adaptive antenna receive system (ADARS, see Figure 2.2), also developed by RADC, made use of the analog-to-digital (A/D) converter technology of its time to accomplish digital conversion *directly* at the antenna, eliminating most of the analog circuitry needed in radios operating in higher frequency bands.

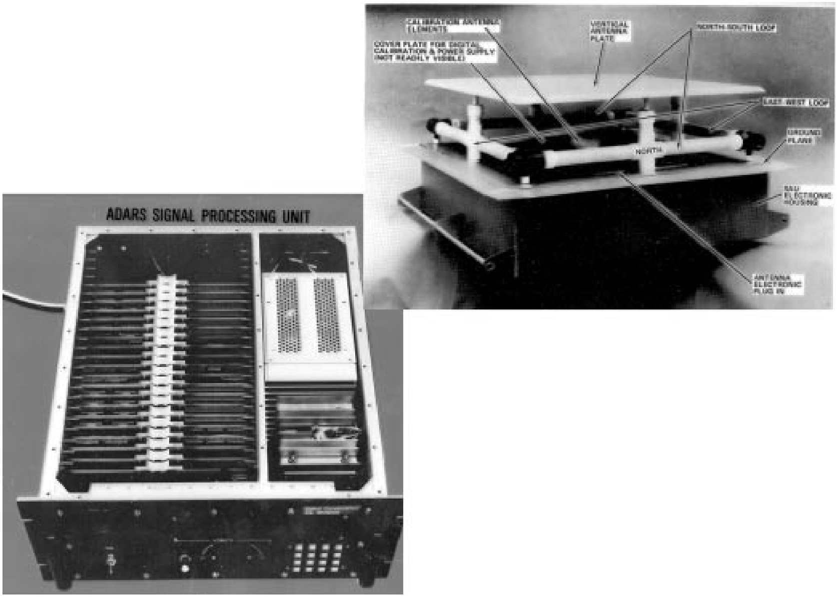

Figure 2.2 Early VLF adaptive antenna receive system (ADARS)

The US MEECN equipment suffered the restrictions imposed by the inherently low bandwidth (High-Q) antennas, and the resultant low data rate throughput. The need for more and more robust communications networks to ensure the delivery of emergency action messages (EAMs) resulted in the technology drive for yet more and more complex (deployable and distributed) network terminals. ‘New Look’, a joint service program sponsored by the Defense Communications Agency (DCA) in the late 1970s and early 1980s, employed BOTH the HF and VHF bands and incorporated three types of diversity: frequency diversity, time diversity, and spatial diversity to gain robustness. New Look made use of spread spectrum RF pulses and frequency hopping across the entire 2–88 MHz range. The use of energy detection, erasure decoding, networking, and message piecing, ensured that information could be passed regardless of jamming, nuclear blackout (heavily ionized D-layer causing extreme absorption), and/or scintillation effects. The extension into the lower VHF band was to enable use of ‘abnormal reflection modes’, off plume-bottoms (scatter from ionized nuclear clouds, similar to scatter off meteor trails), and attain early recovery as blackout conditions abated while the ionosphere began ‘healing’ many hours after a high altitude nuclear burst.

In the 1980s, RADC was examining various methods to enhance ECCM capabilities of tactical radios. To assist in the evaluation of emerging techniques, a jam resistant communications (JARECO) emulator was developed. JARECO [1] enabled an operator to define various waveforms for emulation and download these into an emulation terminal that could provide half-duplex, push-to-talk digital voice communications using the emulated waveform. JARECO could emulate communications countermeasure techniques such as: low-rate digital voice (CVSD, LPC-10), diversity combining, forward error correction (FEC) coding, frequency, time, and code hopping, narrowband cancellation, and various forms of modulation (FSK, MSK, CCSK, or IM/S). JARECO’s master control terminal utilized an IBM-PC/AT (286) to set up, store, and download emulation configurations to several tactical communications terminal units (TCTUs) over an IEEE-488 bus. TCTUs operated as a network, emulating the configured waveform and countermeasure techniques. The TCTUs were programmable and employed four processing elements: a control processor (Motorola 68020), a data processor, a sync processor, and a pulse processor. The latter three processing elements utilized TMS320C25s such that computational loads could be distributed evenly among them. The software was written in ‘C’ and in assembly language. The software was written to be modular, having a common structure, and to enable minimal changes for the different processing elements.

2.1.3 Integrated Communications Navigation Identification Avionics (ICNIA) – The First Programmable Radio

The human–machine interface (HMI) is most crucial in the cockpit of fighter aircraft, and pilots rely on very sophisticated on-board radio systems for communications, navigation, and identification of friend or foe. The growing aircraft sophistication necessitates more and more electronic equipment, which in turn has a severe impact on the aircraft in requirements for adequate size/space, weight, and power to support these new capabilities. Many of these electronic systems perform similar or duplicate functions while adding slightly different services and capabilities. In the 1970s, the Air Force (and the Navy) was looking to improve their avionics suites. In order to resolve space constraint problems, which might have precluded the addition of many new functions and capabilities, the concept of integrating functions into common programmable modules to support diverse services was formed. The Air Force Avionics Laboratory at Wright-Patterson AFB, Ohio, eventually initiated the ICNIA program [2–4] to address this concept.[1] Starting with a series of 6.1 (basic research) and 6.2 (exploratory development) studies, the multifunction, multiband airborne radio system (MFBARS) effort was launched to develop architectures. In 1978, four contracts were let and eventually down-selected to two, for detailed design. In 1983, two ICNIA contracts were awarded based upon the detailed MFBARS designs. Eventually the team of TRW, Rockwell, and Singer developed the ICNIA suite. In 1986, the program was placed under control of the Advanced Tactical Fighter (ATF) Special Projects Office (SPO).

The ICNIA architecture (see Figure 2.3) was split into receive and transmit paths interconnected with data paths, control and spread spectrum busses. A 160 Mbps internal data bus transferred data among the various digital modules. The basic receive architecture was composed of an antenna interface unit, RF switch matrices, multiple multiband receivers and preprocessors, and a VHSIC signal processor, a COMSEC interface, and a VHSIC data processor. The transmit path started at the data processor, and ran through the COMSEC interface and the VHSIC signal processor, into multiple multifunction modulators, into the multimode exciters and finally to the RF switch matrices and antenna interface unit. ICNIA had to emulate numerous military communications, navigation, avionic, and identification capabilities (JTIDS, PLRS, Have Quick, GPS, SINCGARS, UHF-SATCOM, TACAN, FLTSAT, IFF, VOR/ILS navigation, and MLS landing), as well as the more typical communications functions such as: single-sideband HF, VHF and UHF AM and FM.

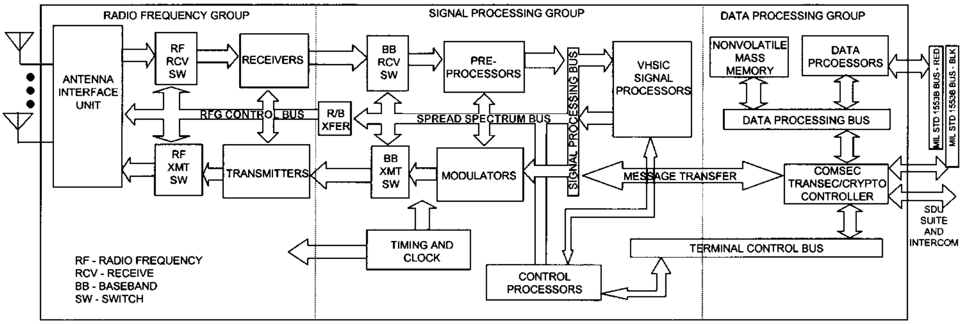

Figure 2.3 The ICNIA architecture

The ICNIA advanced development model's (ADM) RF section covered 2 MHz through 1600 MHz, broken into bands for HF, VHF/UHF and L-band, and had a dynamic range of 117 dB. The ICNIA ADM comprised 4.86 cubic feet of volume, 325 lbs of equipment and came in six enclosures (line replaceable units or LRUs), each of which contained a number of line replaceable modules (LRMs). The RF group contained nine module types with a total of 26 LRMs. Each multiband receiver covered a range of 30–1600 MHz. The receivers were

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[1] Information for the section on ICNIA was drawn from a government memorandum written by M. Minges and J. Arnold of AFRL.

designed as triple-conversion superheterodyne circuits with a noise figure of 3.5 dB. The transmitter group was comprised of separate multimode carrier generators and power amplifiers. The preprocessor LRUs contained a total of eight module types and had a total of 40 LRMs. The preprocessors performed the high-speed waveform-dependent universal matched filter functions. The two VHSIC signal/control processor LRUs contained four module types and had a total of 10 LRMs. The VHSIC processors were capable of > 50 MOPS, had a memory access time of 70 ns, and could accomplish a 1024-point FFT in 1.6 ms. The data processor LRU contained five module types and a total of 20 LRMs. These data processors used the first-generation Singer/Kearfott VHSIC 1750A architecture and were capable of > 2.8 MIPs. The ICNIA ADM (see Figure 2.4) had, in total, 96 modules!

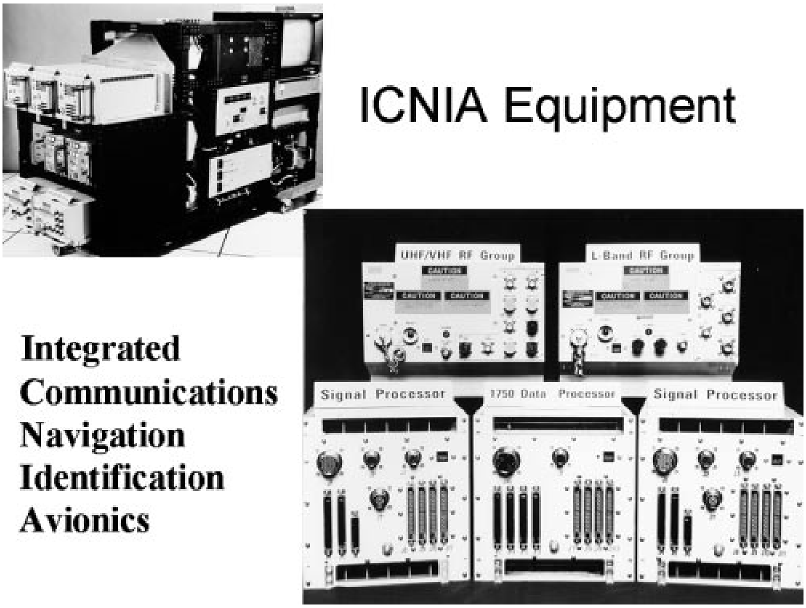

Figure 2.4 ICNIA advanced development module

Distributed control and software design were interlocked across the ICNIA suite. Reconfigurability, fail-safe redundancy, and dynamic real-time built-in-test (BIT) were crucial features of the ICNIA software architecture. Distributed control was the most complex feature of the ICNIA design. There were five levels of control; two ‘outside the box’ and three internal to the ICNIA ADM; levels 0 and 1 were assigned to mission planning and cockpit control, respectively. Inside the ADM, level 2 was assigned for ‘master terminal communications, navigation, and identification (CNI) function configuration and maintenance management’. Level 2 performed various self-tests, noninterruptive (real-time) BIT, and integrated real-time and non-real-time diagnostics, which shared software routines. Level 3 was assigned to ‘resource microcontrol’, and resided in the local microprocessors with their respective read-only memories. Extensive use was made of available software and anything coded specifically for ICNIA was programmed in Jovial, the language of choice for the AF at the time ICNIA began. Later, when the program was placed under the ATF SPO, the remaining new software was programmed in Ada. Some control software was recoded from Jovial into Ada for test and demonstration, but waveform software was left in Jovial.

In September 1987 the ICNIA brass-board demonstration took place. In September 1990, ADM #1 was delivered to the US Army for flight tests on the Army's Blackhawk helicopter. ADMs #3 and #4 were delivered to the Integrated Electromagnetic System Simulator facility at Wright-Patterson AFB, Ohio, in August 1991. The program ended with the delivery of the final report in 1992, and ICNIA became the first programmable radio. This ICNIA technology has formed the basis of the F-22's CNI system.

2.2 The Acorn

2.2.1 Out of the Tactical Anti-Jam Programmable Signal Processor (TAJPSP) Effort Grew the SPEAKeasy Program

2.2.1.1 TAJPSP [5]

Because of the perceived needs for greater interoperability and more capability in a single package, in the late 1980s, the Air Force Research Laboratory (formerly RADC, and later Rome Laboratory), initiated the tactical anti-jam programmable signal processor effort. The driving requirements for the TAJPSP were: a processor capable of simultaneous waveform operation, a system architecture and an operating system optimized for simultaneity, a modular architecture for implementing common functions, maximum use of Ada, and future extendibility. The Army and the Navy, through the Joint Directors of Labs (JDL), became involved in the program and the TAJPSP became a joint, tri-service program. The effort expanded to include an ad-hoc, multiband, RF front end so that the TAJPSP could be tested. In 1990, a contract was competitively awarded to Hazeltine Corporation of Greenlawn, New York, with TRW Military Electronics & Avionics Division of San Diego, California, as a team member primarily responsible for the development of waveform software.

To leverage the most current R&D, TAJPSP bidders were asked to examine a number of existing and related technologies such as: ICNIA, the VHSIC common processor, the AT&T common signal processor (CSP), the advanced on-board signal processor, a VHSIC AJ programmable modem brass-board, the VHSIC technology brass-board, an AF LPI waveform study, the AF jam resistant communications (JARECO) system, the Army's secure tactical AJ (STAJ) system, and the MD-1230 HF modem. Hazeltine and TRW had selected the CSP architecture since the ICNIA operating system could easily be ported. The VHSIC phase II super-chip (CPUAX) was available and looked as if it could form the basis for future growth. The ICNIA INFOSEC module (the AACU, a predecessor to the KOV-5) would form the basis for the TAJPSP security system. The CSP modules were provided by TRW and had been developed under the VHSIC and ICNIA programs. Three major modules of the CSP were the low latency processing element (LLPE), the general purpose processing element (GPPE), and the executive service unit (ESU), which interconnected to the external cryptographic device. Hazeltine developed the multiband multimode radio (MBMMR) system architecture as shown in Figure 2.5.

The CSP and its various elements were contained in the microprocessor subsystem, and the microprocessor interface subsystem was needed to interconnect the various busses to the CSP

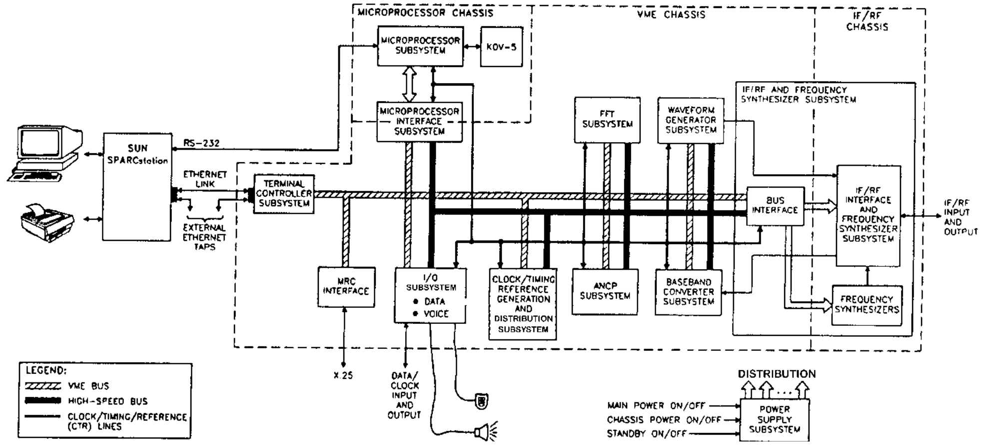

Figure 2.5 TAJSP multiband multimode radio (MBMMR) architecture

elements. The use of the CSP module enabled re-use of ICNIA code in Jovial, Ada, assembly, and microcode. The future of the TAJPSP was tied to the TRW CPUAX VHSIC 'super-chip', and a significant amount of effort was still needed to complete the CPUAX Ada-compiler. The TAJPSP program thus needed to leverage the ATF-SPO F22-CNI (post-ICNIA) program's efforts.

Shortly after the start of the TAJPSP program, the Balanced Technology Initiative (BTI) Office, managed under the Office of the Secretary of Defense (OSD), took a keen interest in what the JDL had initiated. BTI began to provide advocacy and supply additional funding to the program to enable component radio technologies to be further advanced. These components would be added to the MBMMR TAJPSP system as advanced technology modules.

As the MBMMR TAJPSP architectural design was developing; technical concerns grew over a number of issues:

- use of an ancillary, or out-board, KOV-5 (security device) to provide system-wide internal security (INFOSEC) for vehicular and manpack radios, which would eventually need to meet National Security Agency (NSA) security standards;
- choke points within the microprocessor chassis, which were appearing because of the use of TRW's ICNIA-CSP the LLPE, GPPE, and ESU;
- the decision by the F22 Program Office to switch from the TRW-CPUAX to the TI-TMS320C30 processors – leaving little legacy for the CPUAX 'super-chip'.

These concerns led to the decision by the TAJPSP Program Office to have Hazeltine re-engineer the TAJPSP architecture for better INFOSEC implementation and to eliminate the computational and data-flow choke points. These two events (BTI funding, and rejection of the ICNIA processor architecture) marked the emergence of a new program with a new name. 'SPEAKeasy' was born.

2.3 SPEAKeasy – Phase I [5]

2.3.1 A Joint Service Program

2.3.1.1 Balanced Technology Initiative (BTI)

BTI was an OSD scheme to 'balance' the research and development (R&D) science and technology (S&T) investments that were being made in other areas under the air defense initiative (ADI) and the strategic defense initiative (SDI). The objective of the BTI was to hasten the application of advanced technologies to America's most critical and urgent operational needs. BTI projects concentrated on leap-ahead capabilities enabled by emerging technologies. BTI funds were applied to several areas of SPEAKeasy to advance packaging technology and commercial subsystems. Later in this SPEAKeasy Phase I section, the various studies and design initiatives conducted under this program will be described. The Department of Defense (DoD) soon closed the BTI office transferring the BTI technology thrusts to the Defense Advanced Research Projects Agency (DARPA), who continued sponsoring these efforts.

2.3.1.2 Phase I Advanced Development Model Design Objectives

The key design objectives for the first phase of SPEAKeasy were to:

- Implement radio and waveform functions as programmable and as generic (or common) as practical, in order to maximize flexibility and enhance the programmability of the radio system.
- Accomplish the functional decomposition so most functions are allocated to the digital signal processors (DSPs) (which could be shared amongst diverse waveforms and accomplish system tasks while reducing hardware and cost).
- Where functions could not be accomplished within DSPs, these functions would be designed as a group of modular programmable and extensible hardware subsystems (to eventually be replaced with advanced technology modules).
- Develop the system architecture to encompass INFOSEC from the start and adhere to NSA guidelines. Design the system with proper separation of Red and Black data.
- Include a general purpose processor to handle a menu-driven man–machine interface for the SPEAKeasy ADM.

Major tasks that were added to the program included:

- Rehost the functionality that had originally been allocated to the TRW CSP elements (LLPE, GPPE, and ESU) to the latest Texas Instruments DSP, the TMS320C40.
- Develop advanced technology insertion capabilities:
  - an advanced digital signal processing module
  - a programmable INFOSEC module
  - an advanced RF module
- Develop, in accordance with NSA guidelines, interim, non-programmable sub-modules to allow near-term interoperability tests and demonstrations.

2.3.1.3 SPEAKeasy Phase I – ADM Technical Description

The SPEAKeasy ADM consisted of flexible and programmable hardware modules, some containing high-speed microprocessors. The modules were interconnected using several types of busses to accomplish timely interchange of data and to enable control. SPEAKeasy was developed using a 6U/12U VME-bus chassis. The VME-bus was used to accommodate the sending of control signals between modules, configuring ADM subsystems, and for downloading waveform-specific field programmable gate array (FPGA) scripts to the baseband signal processing subsystem.

Referring to the block diagram, shown in Figure 2.6, working from left to right, we see the Sun SPARCstation, which was used to host the intelligent system controller (ISC). The ISC software was responsible for the operation of the HMI, the system configuration control, performance monitoring, and BIT functions. The Sun SPARCstation was connected to an XDS-510 laptop computer over an RS232 interface. The laptop was used to run the C40 tools over a JTAG interface. The SPARCstation also ran diagnostics on the terminal control system (TCS) using an RS232 interface.

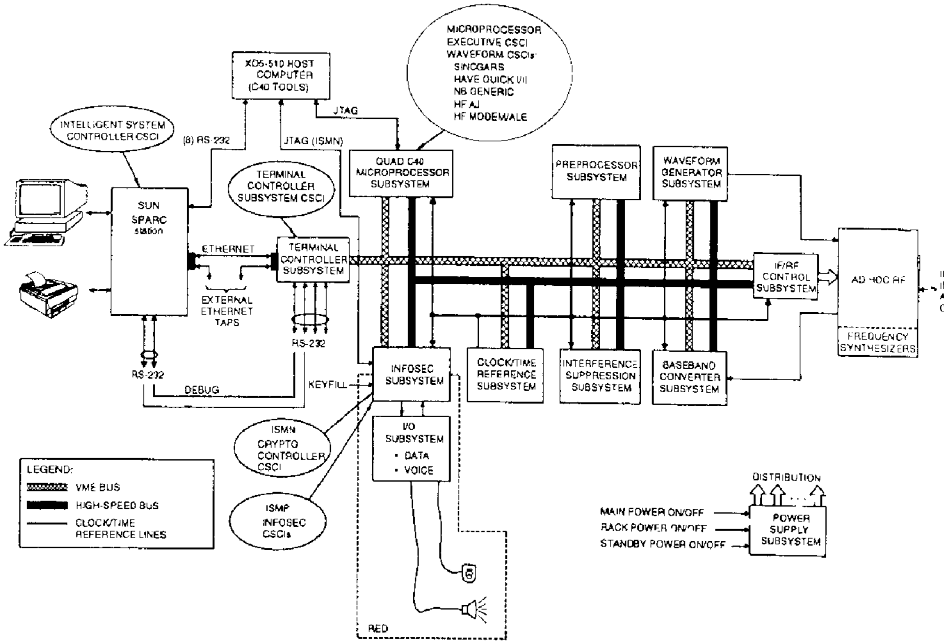

Figure 2.6 SPEAKeasy Phase I block diagram

The TCS communicated, primarily, with the SPARCstation and HMI over an Ethernet. The TCS monitored and controlled the remaining SPEAKeasy ADM subsystems. The TCS functioned as the master of the VME-bus, configured all the other subsystems, and ran BIT over this bus.

The microprocessor subsystem was comprised of four TMS320C40s and implemented the following signal and data processing functionality:

- modulation
- demodulation
- synchronization and control (of narrowband waveforms) and
- post-correlation processing (for wideband waveforms)

The INFOSEC subsystem provided the TRANSEC functions necessary for waveform compatibility and demonstration. A programmable INFOSEC module was designed and ‘vector tested’ independently, but never integrated into the ADM (programmable INFOSEC design efforts are discussed later).

The I/O subsystem interconnected the INFOSEC subsystem with the external analog and digital I/O ports. These included the handsets for analog voice input, the speakers for voice output, and a digital data port that could connect to external data devices.

The clock/timing/reference (CTR) subsystem, via a direct digital synthesizer, provided the programmable system clocks and strobes required for synchronizing processes in the ADM subsystems. CTR signals were passed over independent lines between modules (using the ‘user-assignable pins’ within the VME-bus chassis).

The preprocessor subsystem (PPS) was to be used to satisfy the special requirements of wideband waveform acquisition. The PPS would have accepted wideband-digitized samples from the baseband converter subsystem (BCS), or the interference suppression subsystem (ISS). The PPS would have performed any necessary tapped-delay-line demodulation. The PPS and the ISS designs were never completed, and Phase I did not employ any wideband waveforms.

The ISS was to perform any in-phase (I) and quadrature (Q) frequency-domain transforms needed, and pass the resultant processed data onto the PPS. The ISS would have handled narrowband excision and amplitude probability density function based excision. This advanced capability remained unfunded and its design was never completed. Hazeltine also studied a parallel structure of i860s to provide a more programmable approach; the determination was that 50–100 i860s would be required, which would be cost-prohibitive.

The waveform generator subsystem, the BCS, and the IF/RF control subsystem were designed using a ‘sea of FPGAs’ (in a two-loop controller set-up) in order to ‘program’, using downloaded UNIX-script-files, almost any conceivable waveform. The result of using a ‘sea of FPGAs’ was the requirement to use very large (12U) VME boards. The waveform generator subsystem accomplished modulation functions. The BCS accomplished the down-conversion from IF to baseband. The IF/RF control subsystem provided the necessary interface between the ADM bus system and the analog-RF assets – all of these were fully programmable and configured at waveform instantiation.

The SPEAKeasy Phase I ADM and its bus structure were designed as a four-channel capable system, even though it was never populated with more than two channels. Hazeltine’s custom high-speed bus design was planned to accommodate the implementation of wideband waveforms, although no wideband capability was ever incorporated. The Phase I design was focused on enabling the inclusion of wider band waveforms like joint tactical information distribution system (JTIDS) and a robust low probability of intercept and detection (LPI/D) waveform; these became the primary system drivers. Unfortunately, the ICNIA code would not readily transport a JTIDS capability to SPEAKeasy, and the cost of developing and implementing the wideband preprocessor, and these two waveforms, became cost prohibitive. Therefore, plans for doing so were dropped and no wideband capability was demonstrated.

The ad-hoc RF was a primarily analog subsystem, providing what otherwise would have required special test equipment, to accomplish the IF/RF up and down conversions to enable laboratory, and limited over-the-air, interoperability tests with legacy radio systems.

The SPEAKeasy Phase I ADM (see Figure 2.7) was housed in a 24-inch wide, 6-foot high equipment rack (actual measurements: 70 inches high by 30 inches wide and deep) weighing 250 lbs. The equipment operated at 220 V AC, drawing less than 15 A.

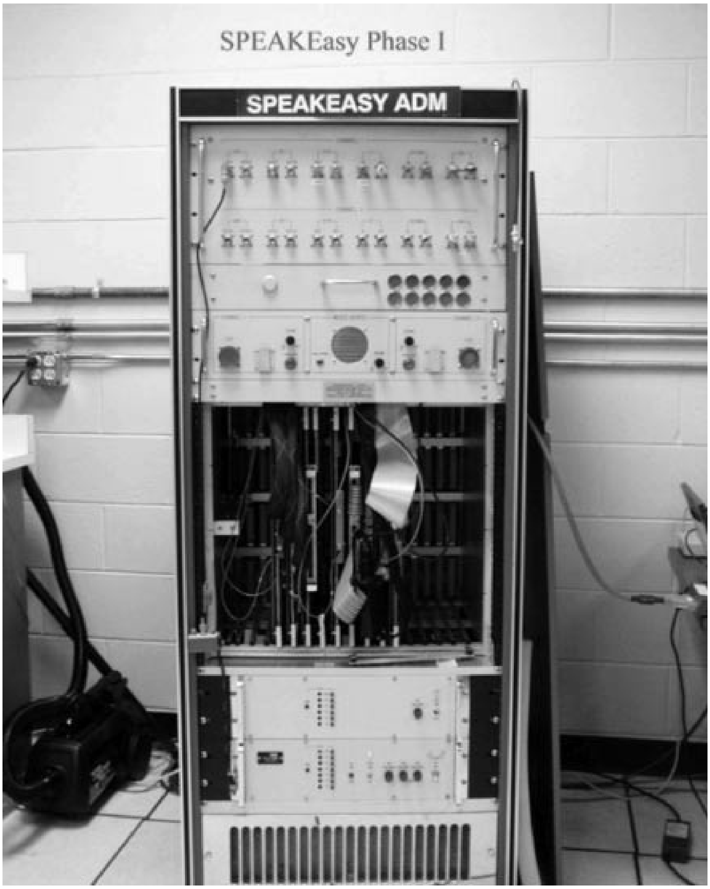

Figure 2.7 SPEAKeasy Phase I advanced development module

2.3.1.4 Various Studies Conducted under SPEAKeasy Phase I

Ten other special studies were conducted under the umbrella of SPEAKeasy. Only a few were taken the next step into an implementation study. Nine were accomplished under the SPEAKeasy contract and one was accomplished under the auspices of the US Army Communications & Electronics Command (CECOM). Under CECOM's management and supervision, the Army awarded a number of studies targeted to examine approaches for a wideband HF, VHF, and UHF antenna.

Hazeltine, as prime contractor for SPEAKeasy Phase I, subcontracted for seven of the nine Phase A design studies. Hughes, of Fullerton, California, and Rockwell/Collins, of Cedar Rapids, Iowa, both were awarded Phase A design studies for a contiguous 2 MHz through 2 GHz RF module. Collins was further awarded a Phase B implementation study that ended with a critical design review. SCITEQ, of San Diego, California, was awarded a Phase A study to examine a *wideband*, direct digital synthesizer for the SPEAKeasy wideband waveform generator. Hazeltine had performed an advanced RF study covering the HF, VHF, and UHF bands, and an advanced processor technology study to examine alternate signal processing architectures for wideband waveform processing. As part of the Hazeltine RF study, APX Resources examined the use of a digital downconverter and concluded that such a converter interfaced to the RF subsystem at a 25 MHz IF would meet SPEAKeasy Phase I requirements. A single 12 bit A/D converter (aided by an automatic gain control circuit), with high-speed sampling and digital decimation filtering, along with wideband anti-aliasing filters and narrowband (70 kHz) filters, to meet co-site specifications, was needed. An A/D converter study was considered, but commercial industry was seen to be leading this area so it was deemed unnecessary.

Texas Instruments (TI), of Plano, Texas, was awarded a Phase A design study for the development of an advanced DSP module. TI was also awarded a Phase B implementation effort and developed a Quad-TMS320C40 multi-chip-module (MCM). The product was marketed for a while afterwards by TI, but is now available in a dual, versus a quad, package. IBM, (Loral) of Manassas, Virginia, was awarded a Phase A study for a high-speed FFT preprocessor module. The study concluded that an FFT module could be implemented in a VHSIC chip on silicon (VCOS) MCM 2 inches square and a half-inch thick. The prediction was that this FFT module would accomplish a 1024 point FFT at 23 kHz (0.0448 ms latency), with the power of 1.9 billion floating point operations per second while consuming less than 5 W. RADC had a separate contract with Syracuse Research Corporation (SRC), not funded by SPEAKeasy, that examined the application of a residue number system (RNS) arithmetic for signal processing. SRC's RNS-FFT predicted a 1092 point FFT at 67 kHz with 50 μs latency. Neither IBM's nor SRC's FFT was developed under SPEAKeasy.

Both Motorola, of Scottsdale, Arizona and Martin-Marietta, of Camden, New Jersey were awarded Phase A studies to examine programmable INFOSEC modules utilizing the cryptographic reduced instruction set (CYPRIS) processor. Motorola would take a conservative approach using physical partitioning and redundancy. Martin-Marietta would explore a riskier design, using context switching to reduce size, weight, and power in their CYPRIS-based INFOSEC module. Motorola was awarded a Phase B implementation effort and developed a SPEAKeasy INFOSEC module (SIM) on TWO, 12U VME-bus boards. The SIMs were successfully 'vector tested', provided input with known outputs, but were never integrated into and tested with SPEAKeasy terminals.

Two advanced technology simulations were accomplished. One related to exploring multiple access techniques and simulating network protocol compatibility with the proposed SPEAKeasy LPI/D waveform developed at the AF lab, in Rome, New York. The other was focused on quantifying the performance of combining an adaptive non-linear correlation process with a narrowband excision process. The Applied Physics Lab of Johns Hopkins University performed the simulation and concluded that the combination was better than either process by itself, and that 'punched-hole' excision showed a 2 dB improvement over interpolation.

2.3.1.5 The 1993 Multiband Multimode Radio Panel[2]

In May 1993, Mr George Singley, then Deputy Assistant Secretary for Research and Technology (Office of the Assistant Secretary, Army), raised concerns regarding the need for an accelerated MBMMR program. Army CECOM convened a joint service panel to look at the near-term Army requirements for an MBMMR, identify an engineering development model (EDM) program to accomplish an MBMMR ATD, and assess MBMMR requirements on existing Army ATD programs. Also created was a technology assessment subgroup to examine the technology available to support an Army manpack MBMMR by 1998. The subgroup concentrated on the following topic areas: antennas, RF front end, open architecture, simultaneous operation, processing, networking, security, power consumption, programmability, and packaging. The MBMMR study lasted about a month and resulted in the following conclusions. The technology assessment ascertained that although the technology of the time supported product development in 1998, such a product would not be as programmable as promised under the SPEAKeasy program, and that multiple antennas would be needed (2–30, 30–450, and 450–2000 MHz). Wideband waveforms as used for JTIDS and the VRC-99, would require separate application-specific integrated circuit (ASIC) devices for preprocessing of these signals. It was determined that utilization of emerging SPEAKeasy technologies to accomplish either an accelerated or objective MBMMR program was the best path to the Army's MBMMR, and the user community strongly supported the programmable SPEAKeasy architecture for low rate initial production (LRIP) in 2005. There was no approved requirement for an interim radio, or an approved requirement for a SPEAKeasy MBMMR by 2005. The panel recommended that the Army continue its participation in SPEAKeasy beyond 1994 and to focus a Phase II Joint Service SPEAKeasy program toward providing the Army with demonstration models to support other Army ATDs in the FY99 timeframe.

2.3.1.6 SPEAKeasy Phase I Interoperability Tests and Demonstrations

In August 1994, 'proof-of-concept' demonstrations were conducted for personnel invited by the government. The purpose of these demonstrations was to:

- highlight programmability, flexibility, reconfigurability, and the maximum use of programmable signal processors;
- illustrate the capability to communicate with multiple backward-compatible (legacy) systems – simultaneously; and
- demonstrate unique SPEAKeasy capabilities.

During these demonstrations the following capabilities were proven: interoperability with legacy SINCGARS and Have Quick I/II radios (both operating in their respective bands and hopping modes), and automatic link establishment (ALE) and HF modem (transmission only). Two simultaneous waveform demonstrations were also shown: SINCGARS on channel 1 and Have Quick on channel 2 operating simultaneously, and a simultaneous operation using Have Quick on both channels. A demonstration of an unattended gateway (SINCGARS to Have Quick, hopping in the VHF and UHF bands) was highlighted. In this demonstration,

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[2] Information in this section was drawn from the MBMMR final report (dated July 2, 1993) provided to Mr George Singley by J. Oneffur and Major R. Nelson of CECOM/RDEC.

an operator of a SINCGARS radio keyed his microphone and started to speak, the SPEAKeasy radio detected the VHF reception of SINCGARS, decoded the CVSD voice, and sent the analog voice into a Have Quick channel, where it was transmitted on AM at UHF. A unique programmability demonstration was conducted to prove that a new waveform could be quickly generated, coded and downloaded for use. A ‘modified SINCGARS’ waveform, with a 1600 bps 100 ms burst, was used to place a 1 kHz ‘beep’ in the waveform. This ‘new’ waveform was downloaded into and transmitted by a SPEAKeasy ADM interoperating with a standard SINCGARS radio, from which the periodic ‘beep’ could be heard. This ‘beep’ represented a 100 ms time period that could be used, as an example, for selective addressing within a SINCGARS net. The use of standard audio WAVE file format (‘.wav’) for storing digital audio (waveform) data was used to enhance the HMI for ALE. Voice ‘.wav’ files were used to provide an audio-alert, to the SPEAKeasy radio operator, for changes in status.

The SPEAKeasy program was chosen to participate as part of the Joint Warrior Interoperability Demonstration (JWID) held at ‘Fort Franklin’, Hanscom AFB, Massachusetts in September 1995. In preparation for this exercise, SPEAKeasy ADMs were modified to enhance demonstration capability in the field. A ‘generic bridging’ mode was implemented to allow the SPEAKeasy ADMs to ‘bridge’ two remote radios, operating different protocols, to communicate with one another. Signal detection messaging functionality was added to the waveforms; this was used for an indication that a signal had been received (the preamble detection, or the squelch capture depended on the protocol in use). To enable channels to be automatically placed in a transmit mode, special control logic was added. A conference mode was also added to allow a SPEAKeasy operator to monitor and/or participate in ‘bridged’ communications. The SPEAKeasy HMI was modified to include a special bridge menu, and to simplify the operation of the ADM.

Three weeks of demonstrations were conducted during the JWID-95 exercise. The goal was to interoperate with as many on-site radios as possible. The demonstrations were conducted with over-the-air transmission and reception, using standard HF, VHF, and UHF antennas (a small whip antenna was used to cover the 90–200 MHz band). SPEAKeasy successfully executed time-of-day transfers and performed Have Quick hopping operation with the command and control aircraft at the site. Interoperability was demonstrated with: a ‘Scope Shield’ handheld SINCGARS radio, a standard citizen’s band radio, and in ‘receive-only’ with the air traffic control (ATC) tower. ATC voice traffic was also bridged through a SPEAKeasy ADM to a standard SINCGARS radio. Bridging between a standard hopping SINCGARS radio and standard citizen’s band radio, and between standard Have Quick and SINCGARS hopping radios was also conducted during JWID-95. The SPEAKeasy demonstrations focused attention on the capabilities of a programmable radio asset; more than 700 people witnessed SPEAKeasy’s capability demos during JWID-95.

2.3.1.7 Planning for SPEAKeasy Phase II

The successful ‘proof of concept’ demonstrations of SPEAKeasy technology in August 1994 led to planning for the second phase of the program. SPEAKeasy Phase I was concept exploration, the Phase I equipment were planned to be laboratory prototypes, and thus no attempt was made to ruggedize or miniaturize them. The ad-hoc RF was meant only as a crude method enabling the verification of waveform compatibility with legacy radio equipment. The objective of Phase II was to develop field capable prototypes with full RF capability that would be able to participate in exercises by receiving and transmitting over-the-air. The Phase II program was to be structured to strongly leverage Phase I designs but not require that they be followed. Maximum use of commercial off the shelf (COTS) components, the use of non-proprietary busses, the implementation of an open architecture, and the inclusion of INFOSEC and wideband data waveforms became additional Phase II objectives. There were six selection factors advertised for the Phase II program:

- Factor 1 – Modular Definition of Open System Architecture: The system's architectural design was to have modular, functional parts, having well-defined functional requirements, and non-proprietary commercial interfaces. The modular definition was to maximize, at both the component and module level, the applicability of future multi-source non-developmental item (NDI) and COTS products.
- Factor 2 – Information Security (INFOSEC): Security designs were to adhere to accepted security guidelines for COMSEC, TRANSEC, Key Management, and Quadrant. Capabilities for Benign Fill, Over-the-Air-Rekey, and Over-the-Air-Download had to be considered in the system design. The design was to provide for the growth potential for future capabilities.
- Factor 3 – Programmability and Reprogrammability: The system design was to provide for the operation and maintenance of a software programmable radio. Consideration was to be given toward a waveform development environment (WDE) sophisticated enough to support waveform development and coding during Phase II and beyond.
- Factor 4 – Simultaneity and Internetworking: Designs were to support the required four simultaneous (4 narrowband, or 2 narrowband + 2 wideband) waveforms, giving adequate consideration to potential EMI, EMC, and co-site problems. The design needed to support the required internetworking and bridging functions.
- Factor 5 – Implementation: The design was to be achievable within the desired form, fit, and power constraints of Phase II and adequate consideration was to be given to other embodiments. Plans were to include the early demonstration of capability, include modular P31 enhancements, and the spin-off of technology to other programs.
- Factor 6 – Management: The organization and structure, for a team of multiple players, were to ensure the early identification and resolution of problems, maintenance of schedule, and control cost.

To ensure the greatest possible technology transition from Phase I into Phase II, about 100 reports from SPEAKeasy Phase I were duplicated (two copies) and placed in a 'read library' for use by all Phase II potential bidders. Local copying of any and all (unclassified) reports was allowed. A dozen or so companies reviewed SPEAKeasy Phase I documentation in preparation for this second phase and many opted to make personal copies. A requirement to participate in a government–industry forum on open architecture software radios (that the SPEAKeasy Program Office hoped to create) was listed as a requirement of the Phase II effort. That forum has today evolved into the SDR Forum (formerly MMITS) and is discussed in Chapter 3

2.4 Future Multiband Multiwaveform Modular Tactical Radio (FM3TR)

2.4.1 Establishment of the FM3TR LTTP

In December 1991, the four power Air Senior National Representative (ASNR) Long Term Technology Program (LTTP) working group was briefed by the US Air Force ASNR on the SPEAKeasy (Phase I) program. The US proposed MBMMR as a suitable topic for LTTP consideration and agreed that appropriate representatives from France (FR), Germany (GE), and the United Kingdom (UK) could attend SPEAKeasy meetings as observers, with the objective of determining if an LTTP topic area for MBMMR was desirable. A year later, in September 1992, the ASNR LTTP received a briefing on SPEAKeasy by the AF program manager who was asked to draw up a list of topics for potential LTTP collaboration. Starting in September 1993, a technical group comprised of all four nations began to work together to establish a detailed program of work in the MBMMR topic area. In April 1996, a supplement to the ASNR LTTP memorandum of understanding (MOU) was added to establish the FM3TR LTTP:

> The objective of the FM3TR LTTP is to develop and assess relevant radio technologies for inclusion into tactical radio systems. This is to support the standardization of techniques, procedures and methodologies for the development of a cost effective advanced technology radio.

The scope of work of this project included: a definition of common tools to support transportability among independent architectures and development of advanced technologies, which would aid future reductions in life cycle costs. The FM3TR technical group was to use parameter exchange and other processes to enhance interoperability by implementing common waveforms (e.g. STANAGs). Radio capability and performance was to be enhanced through application of new technologies. Programmability, applicable to flexible and reconfigurable modular system designs, was to be addressed. The detailed technical topic areas were defined as: radio and software architectures, RF and digital signal processing, communications management and interconnecting networks, and the HMI. The FM3TR LTTP provided an international arena in which SPEAKeasy could demonstrate the benefits of a reprogrammable open systems architecture radio system.

2.4.2 FM3TR Successes

France, Germany, and the United Kingdom were all pursuing similar technology efforts to introduce these new concepts in the European domain. The FM3TR LTTP technical group met regularly to discuss national programs, the state of technology, and the collaborative effort to demonstrate interoperability of national software radio assets. The FM3TR LTTP technical group designed a test waveform so that each nation could develop their own radio architecture and system implementation, and eventually verify through tests and demonstrations that programmable radios could swiftly achieve interoperability. The FM3TR test waveform was designed to be an unclassified, multiband (VHF and UHF), frequency hopping waveform (at 250 hps and CVSD for voice) with programmable parameters controlling its operation. At its 12th meeting, in June 1998, held at AFRL's Rome, New York, facility, a major milestone was achieved when the UK and US prototypes were able to interoperate utilizing the FM3TR test waveform. The UK modulated and transmitted digitized voice, and the US was able to acquire, receive, demodulate, and hear the voiced message. The UK employed a newly developed GEC–Marconi–Hazeltine programmable modem (transmitter), and the US employed its SPEAKeasy Phase I system.

A little over a year later, during the week of November 8, 1999, an international interoperability demonstration of software radio systems was held at the SEL Defense Systems facility in Pforzheim, Germany. Germany had an SEL-developed prototype terminal, the UK used the software transmitter developed by GEC–Marconi–Hazeltine, and the US used a newly created software radio development system (SoRDS), jointly developed by AFRL and the Rome Research Corporation (RRC). This demonstration was the realization of multiple implementations of software radios performing a complex, frequency hopping waveform. Although the test waveform was developed from the single FM3TR waveform specification, it was implemented in extremely different hardware and software architectures. The three national systems were designed, and the ‘waveform application’ was developed, without pre-coordination between the actual contractor-developers. All modifications necessary to enable system interoperability were implemented on-site in Pforzheim with only minor changes in software. The three systems were correctly acquiring, tracking, and sending and/or receiving data with the other systems within 8 hours of the initial set-up. The frequency coverage of the systems included both the VHF and UHF military bands (30–400 MHz). The UK (Marconi – now BAE Systems) system transmitted voice at the stated hop rate with selectable hop sets of up to 40 frequencies. The German (SEL) system was able to transmit or receive data files using the specified waveform with hop sets containing up to eight frequencies. The US (SoRDS) system was able to transmit or receive voice or data, using the specified waveform with selectable hop sets containing up to 40 frequencies. This demonstration clearly established the viability of deploying SDRs that meet different operational missions, and enable the expeditious attainment of interoperability between diverse, independently developed, national communication systems.

2.5 SPEAKeasy – Phase II

2.5.1 PC of the Radio World

In April 1995, the SPEAKeasy Phase II request for proposals (RFP) was released to industry. The AF agreed (at the insistence of DARPA) to pursue Phase II as an ‘Other Transactions’, following acquisition reform and steering away from the conventional DoD-5000 contractual arrangements. SPEAKeasy Phase II would seek teaming arrangements since it was felt that no one company held sufficient expertise alone to successfully accomplish all that was planned under Phase II. Three technical proposals were received in May 1995. Together, the three teams represented 25 companies and were evaluated by experts from DARPA, Army-CECOM, NRaD, the NSA, the OS-JTF, and AF Research Lab (formerly the Rome Laboratory). On June 29, 1995, an award was made to the team comprised of Motorola, ITT, and Lockheed-Sanders, as well as about nine other companies and universities in subcontractor partnership.

2.5.1.1 Scope and Objectives of SPEAKeasy [6]

The SPEAKeasy objective was described in the Phase II RFP with the words:

> The SPEAKeasy concept introduces a revolution in the prevailing architectural infrastructure of radio communications systems. SPEAKeasy centers about a well-defined standardization of interfaces and functions that allows interoperability and flexibility of radio systems not previously attained. It is an 'open systems' architecture, focused on modularity by radio function (not by waveform), which has a library of common modules.

The RFP further described the program stating:

> It is the government's objective to satisfy the largest market possible with the SPEAKeasy Architecture. It is desirable to have a design that is applicable to as many platforms (aircraft, ship, tracked-vehicle, manpack, etc) and form-factor (SEM-E, VME, 1553B, etc) as possible.

The RFP recognized that a single design would not be amenable to all possible platforms and form-factors, and that trade-offs for performance and economy might be necessary for some applications. Therefore, the thrust was to define an architecture that could be implemented in as many embodiments as possible (for military, federal, and civil customers, see Figure 2.8), while achieving adequate performance and reasonable cost.

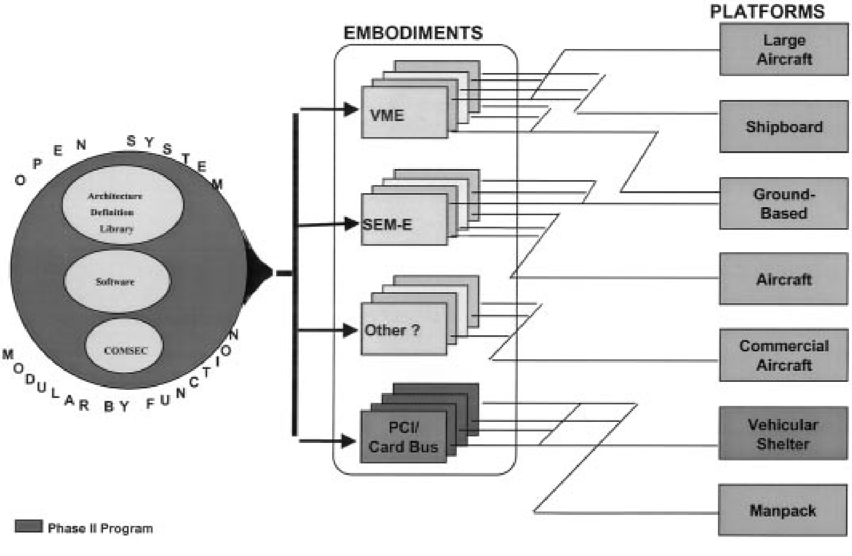

Figure 2.8 Architectural embodiments

The concept was for SPEAKeasy to become the 'PC of the Radio World' – having the flexibility, pervasiveness, and the cost effectiveness of a modern home and office PC. Therefore, the SPEAKeasy Phase II effort was an architecture development and demonstration program, with a functional specification as the deliverable. The actual hardware designs and implementations were not purchased (nor were they deliverables) under the agreement, and the government encouraged the use of proprietary, state-of-the-art, and commercial technology at the module and sub-module level. It was anticipated that the SPEAKeasy architecture would enable a communications system to be 'more than just a radio' and eventually incorporate other processing functions to become an extremely capable and generic ‘information transfer system’. SPEAKeasy was to develop a ‘common architectural framework’, which all the Services could eventually pursue, potentially decreasing purchase-costs by increasing the number of unit-purchases, and through the deployment of common equipment streamline documentation, training, maintenance, and thus reduce life cycle costs (LCC) dramatically.

2.5.1.3 Modular Open Architecture [6]

SPEAKeasy pursued a modular open-system architecture focused on modularity by function (not by waveform or channel). This was so that module improvements (replacements) could be made (with advancing technology) without the need for a costly system retrofit or redesign. In this implementation, ‘modules’ could be either hardware or software to accomplish a set of functions. Technological transparency was the goal. This was to be characterized by standardized functional modules, independent of waveform or packaging, widely accepted open interfaces, which would interconnect the system bus fabric through a tailored adapter (see Figure 2.9), altogether enabling alternate embodiments and implementations in a bus-independent manner.

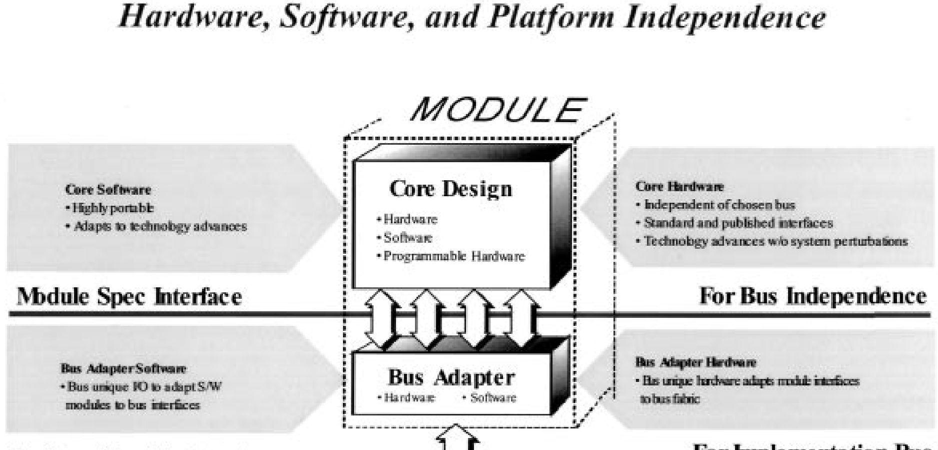

Figure 2.9 SPEAKeasy open modular hardware/software

Using open-design application programming interfaces (APIs) could also provide functional independence from both hardware and software and ease portability between processing platforms and vendors. The RF module would accomplish antenna selection, transmit/receive switching, tuning, co-site filtering, up and down-conversion, automatic gain control, reference generation, and anti-aliasing, etc. A modem module (hardware or software) would perform functions such as analog and digital conversions, interference excision, spreading and despreading, modulation and demodulation, correlation, error correction, timing generation, TRANSEC, and frequency hopping control. The INFOSEC module would be the passageway between the deciphered and enciphered data paths and processes, handle encryption and decryption, key management, and security authentication and validation. An internetworking module would include vocoding, routing, interfaces for voice bridges and gateways for data, and limited message processing. The HMI would provide operator control, monitor and display, initialization and system configuration, and BIT functions.

SPEAKeasy introduced the concept of ‘virtual radio channels’. SPEAKeasy systems resources were NOT to be established as fixed channels, with specified modules in a specified sequence to create a voice or data channel from I/O to RF. SPEAKeasy modules were a ‘pool of resources’ to be assigned at instantiation to comprise a channel that would exist for the duration of its use until turned off or altered by the operator. When the system was turned on and configured again, it might configure channels differently assigning different resources (modem, I/O, INFOSEC) than it had the first time. The use of a resource-pool allowed re-assignment of resources to new or higher priority channels as dictated by the operator and for graceful degradation. The RFP indicated that SPEAKeasy ADMs were to support the simultaneous use of up to four narrowband channels (or two wideband and two narrowband).

2.5.1.4 INFOSEC

Information security was a key element within SPEAKeasy. INFOSEC design should not be an ‘aftermarket’ add-on. An INFOSEC module enforces Red/Black separation for both data and control and reaches into every corner of the system. Such a capability needed to be as programmable as the rest of the SPEAKeasy system. As different waveforms were instantiated, their corresponding security measures (encryption/decryption and the associated hopping algorithms) would also need to be established. SPEAKeasy would need to manage and control keys and algorithms, provide storage, retrieval, and rekey functionality for every secure or ECCM waveform. Plain-text-bypass for ‘virtual channels’, secure voice-bridging, and secure gateway functionality were new INFOSEC capabilities that were derived requirements for SPEAKeasy.

2.5.1.5 Reprogrammability

While many existing radios (in 1995) may have been computer controlled, or operated under microprocessor control from software stored in memory (ROM, EPROM, etc.) they were NOT ‘reprogrammable’ such that they could accept new software or add new functionality via software download, especially not downloads over-the-air to fielded terminals. In most radio systems, changes in frequency allocation, alterations in hop sets, modifications in RF regulations (i.e. channel bandwidth or filtering requirements) and added interference cancellation capabilities would result in very time-consuming and costly redesign. SPEAKeasy was to accommodate all these types of changes and to accomplish these with minimal hardware (field kit) changes and/or software download via a PC connection, or through an over-the-air distribution of modified or new code. Changes could therefore be made in situ, would take only seconds, and would be much, much less costly.

2.5.1.6 Simultaneity and Internetworking

SPEAKeasy ADM would need to provide very many waveforms, modulation types, coding methods, protocols, and INFOSEC algorithms (see Figure 2.10) and support the operation of these in various combinations, simultaneously, in multiple channels.

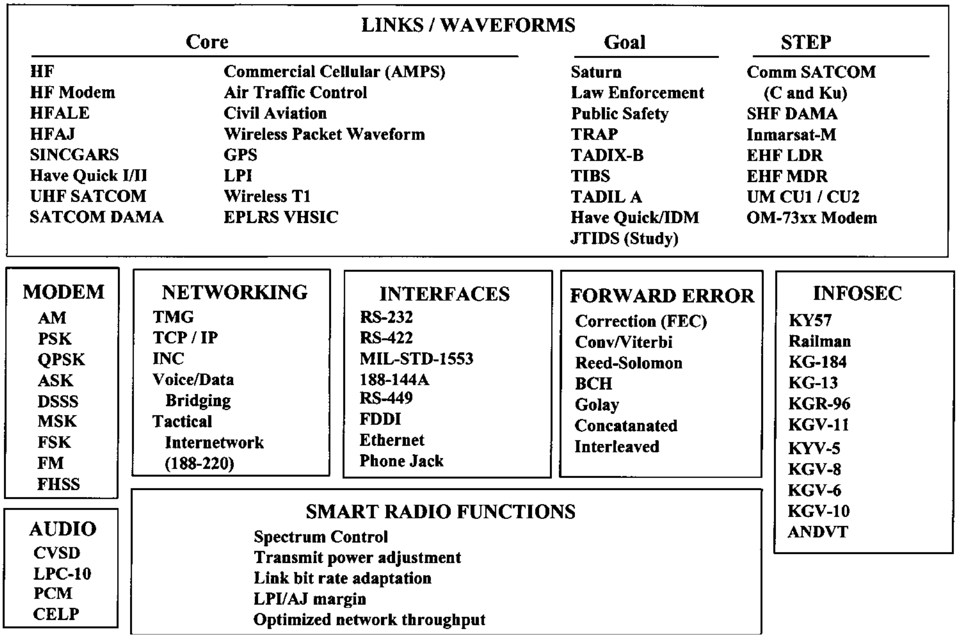

Figure 2.10 SPEAKeasy capabilities

The SPEAKeasy ADM would need to provide mechanisms to interconnect diverse and disparate voice and data circuits in order to provide the voice-bridging and data-gateway functions envisioned. The frequency translation, modulation changes, transcoding, and whatever protocol changes necessary would need to be accomplished seamlessly and without operator intervention once the channels were instantiated. The potential for timing difficulties and self-interference was serious and needed to be addressed in both the architecture and the implementation. The Army had driving requirements, under their digitization of the battlefield, to ensure that radio circuits could be networked and data could be routed in and out via either end of the radio system, the RF or the I/O.

2.5.1.7 Software Design

As mentioned earlier, the software architecture for SPEAKeasy needed to be as open as the hardware architecture. Hardware was to be described in VHDL and software coded in a higher order language (such as Ada or C + +). Ada was NOT a requirement for SPEAKeasy Phase II. The concept was to develop functional modules in software and develop a re-use library. Providing a reprogrammable radio system was only half of the solution to a fully flexible and reprogrammable communications asset. The ability to modify or create new software for the system, and to do it easily, quickly, and inexpensively was the second half of the solution. An integrated software support environment was seen as the key to the eventual success of a reprogrammable system. Through an integrated software support environment new capabilities could be created, packaged, and downloaded, making the fielding of military capability enhancements rapid and affordable. Since platform integration costs were typically more expensive than any single item installed or modified, enhancements made without affecting the platform would save huge amounts of time. This would allow affordable technology upgrades and it would lower the system LCCs, in comparison to the typical military communications systems, which were modified time and time again (i.e. Have Quick and SINCGARS) at substantial additional cost.

2.5.1.8 Human–Machine Interface (HMI)

Operation and control of a reprogrammable radio needed to be simplified, especially since a single terminal would emulate so many radio-waveforms. It was envisioned that there would be multiple levels of control required and that the HMI would need to adapt for each. The ADM required basic radio-operator control, maintenance-operator control, reprogrammer/ network-administrator control, and remote control capabilities. Each would require additional capabilities that were not shared. A radio operator would be prevented from accidentally reprogramming the radio, the maintenance operator would have access to diagnostic capabilities that a radio operator would not, and so on. The SPEAKeasy Phase II effort was thus required to examine these issues and provide solutions.

2.5.2 The SPEAKeasy Phase II Program and ADM Implementation

2.5.2.1 Program Evolution

Motorola's SPEAKeasy team originally planned for four model-year proof-of-principal demonstrations with evolving capability and field-worthy demonstration hardware for the last 2 years (summers of 1998 and 1999). However, within the first 6 months, the government changed the direction of the program and pressed for an early demonstration of capability. DARPA, who had funded and supported the SPEAKeasy program for 3 years, had decided that the maturation of a complete radio architecture was a stage beyond 'development of breakthrough technologies' and that it was time that they transitioned their efforts to the Services. One final capability demonstration during a major exercise would enable them to defend their transition and redirect their efforts elsewhere. DARPA provided the funding to alter the program, enhance the model-year-1 terminals (originally intended to be laboratory units) for field use in the Army's planned Task Force XXI Advanced Warfighter Experiment (TF-XXI-AWE), at Ft Irwin, California. This meant freezing the model-year-1 design, and postponing those tasks under the umbrella of long-term design, to concentrate all personnel and resources on the near-term goal of completing field-worthy equipment. TF-XXI-AWE was, at that point, only 12 months away. Model-year-1 terminals would be two-channel, half-duplex, units with remote control heads in order to enable Tactical Air Control Party (TACP) personnel (using SPEAKeasy terminals along with their GRC-206 communications suites) to move away from their vehicles while performing their aircraft control functions for close air support (CAS) during TF-XXI-AWE. Ancillary equipment, antennas, multi-couplers, power supplies, and an S-280 shelter with equipment racks were needed and required immediate interfacing to the SPEAKeasy Model 1 ADMs. Obviously, many new tasks were added, many ongoing tasks were hastily completed, and many long-term design tasks were dropped and never picked up again.

2.5.2.2 Advanced Development Model Overview [7]

Motorola had (under company funds) been developing a wideband, 2 MHz–2 GHz, RF transceiver module using a homodyne-based design. This transceiver design was expected to eliminate the complexities created by simultaneous operation of multiple channels. Typical heterodyne approaches require precise intermediate-frequency plans in order to cover a large (multiband) frequency range. Since these RF modules were half-duplex devices, full-duplex operation would require the use of two half-duplex channels. Refer to Figures. 2.11 and 2.12.

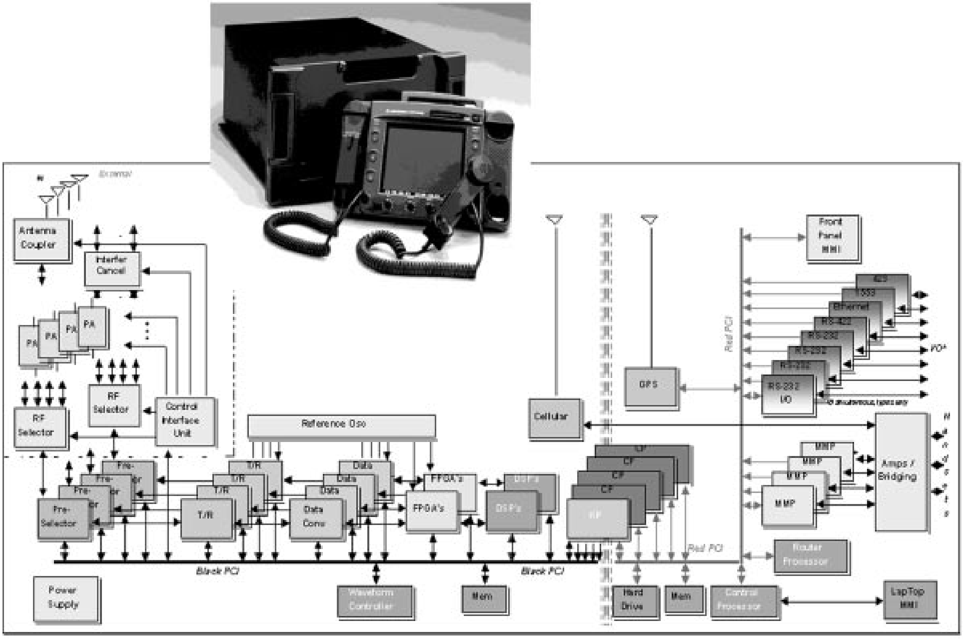

Figure 2.11 SPEAKeasy Model 1 ADM block diagram

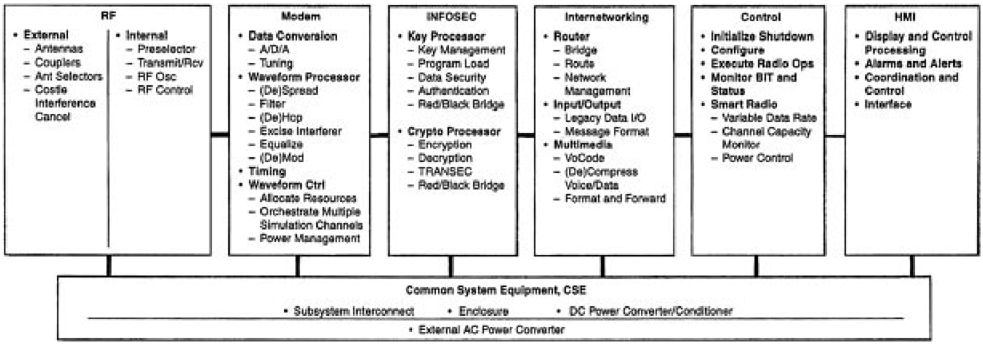

Figure 2.12 SPEAKeasy functional allocation

RF subsystem functions included antenna switching and coupling, interference cancellation, amplification, diversity combining, filtering, and up/down conversion. RF analog circuits and components were connected to an ISA bus and included the external RF section, antennas, power amplifiers, couplers, and selectors. Their system implementation required three busses, the ISA bus for the RF and two personal computer interface (PCI) busses, one for the Black (encrypted data) and one for the Red (unencrypted) side of the isolating INFOSEC module. Waveform processing and both digital and analog conversions took place in the modem section, which was the chain of transmit/receive modules, data converter, FPGA, and DSP modules, that were all interconnected via the Black PCI bus. The motherboards were COTS products, such as used in common personal computers. In the modem section was where spreading and despreading, equalization, hopping/de-hopping, tuning, resource allocation, and power management were accomplished. The modem processing design used TMS320C40s, augmented with FPGAs to increase speed and decrease latency for certain waveforms. It employed software-programmable components with hardware that was assigned a priori to channels. Resources could be allocated to any of the channels based upon the specified waveform when the channel was assigned. Reallocation of channels could be performed dynamically for one channel without disrupting another. The key processor (KP) and the crypto processors (CP) provided INFOSEC services and interbus communication. Each virtual channel required its own CP, but information flow did not require KP intervention after the channel had been instantiated. The KP handled storage and maintenance of various keys, while the CPs encrypted and decrypted baseband data and developed the TRANSEC bitstreams. The internetworking section handled the voice-bridging, data routing, and network management functions. It also performed the I/O and multimedia functions such as vocoding, data formatting, and compression and restoral. The internetworking section processed channelized voice using multimedia processors. The control section executed the start-up and shut-down functions, configuration (of both the router and radio, and for the I/O), downloading, and BIT and system diagnostics. Any ‘smart radio’ functions (such as variable data rate, channel monitoring, and power control) would have been handled in this section. The HMI provided the system level user interface and handled graphical display, alarms, and alerts. The HMI was implemented using an embedded Fujitsu Stylistic 1000, pen-based palm-top, AMD-486DX computer operating under Windows 95. The HMI also provided the mechanism for remote control with the unit’s ability to be removed from the radio chassis and extended on a long cable via its communications port. The ‘common system equipment’ consisted of the enclosure with all the power supplies, cooling fans and thermal management circuitry, electromagnetic interference shielding, and various shock and vibration dampers.

The SPEAKeasy Phase II ADM primary system software modules are shown in Figure 2.13. There were nine primary software modules in the Phase II design.

The HMI’s computer software module controlled the display, keyboard, pen, and other I/O devices and also replicated the legacy waveform operator functions. The control computer software module started and shut down the system. Under script or operator control, it handled channel set up and waveform instantiation. It was also the system manager, maintained the status, and was the conduit for information between the HMI and the rest of the system. The multimedia processing computer software module performed the vocoding, compressed and decompressed data, and handled the voice bridges between channels. The routing computer software module performed routing, handled protocols, and interconnected

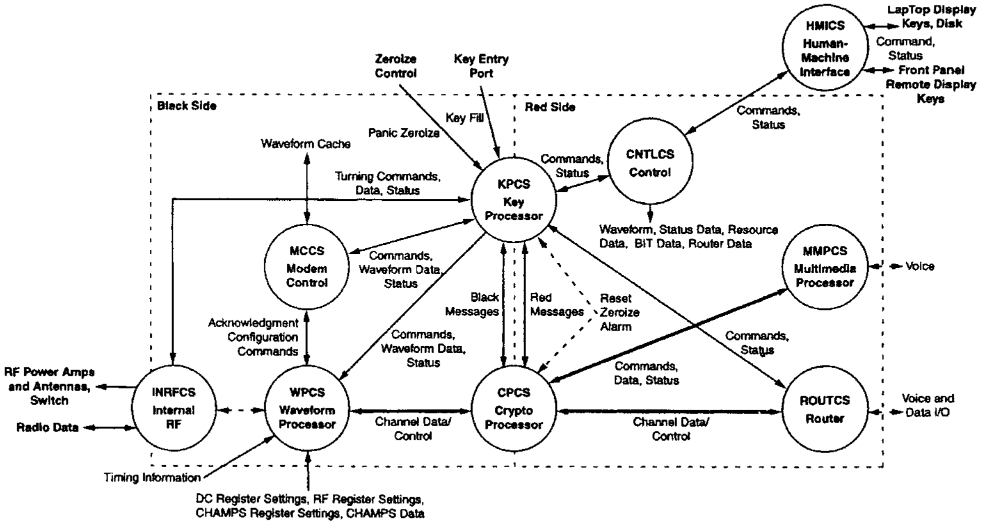

Figure 2.13 SPEAKeasy software control and data flow

landline ports, and serviced external router requests, routed IP packets, and terminated IP protocol stacks. It was the local communications control processing servicing the RS232, FDDI, Ethernet, and MIL-STD-1553 interfaces. The key processing computer software module maintained cryptographic key control, monitored, managed, and controlled the flow of data across the Red/Black INFOSEC boundary. It was the only entry into the system for messages between the system control module and other system modules. The cryptographic processor computer software module was assigned to a specific channel by the KP and provided the virtual connection between the red and black bus for that channel. It also supplied real-time encryption and decryption, and TRANSEC bit generation. The waveform processing computer software module was executed on the DSPs. Its function was waveform-specific and it was established at instantiation. It handled all the typical waveform functions such as: spreading/despreading, modulation/demodulation, interleaving/de-interleaving, framing/deframing, equalization, and synchronization. The modem control computer software module allocated resources during instantiation and its state machines controlled the function of resources during operation. The internal RF control software module was strictly limited to control functions for the analog RF such as reconfiguring transmit/receive, setting power levels, setting local oscillator frequencies (for up/down conversion) and switching functions for external equipment (antennas, preselectors, interference cancellers, etc.).

Since there was no centralized operating system within the SPEAKeasy architecture, the communications between software modules employed message passing over the PCI bus. The message passing was asynchronous over multiple channels and the associated control functions were executed concurrently. The protocol used three layers of abstraction: application layer, communications layer, and the link layer. The application layer consisted of waveform software and all the software modules shown in Figure 2.13 resided here. Control messages were virtual function calls. Included here were all the command, status, and parameters for the data and control categories. The communications layer was actually an infrastructure layer that utilized the link layer services to establish a message passing connection with the API used by the waveforms. The communications layer established links among system resources, automatically found and identified devices on the bus at power-up. The communications layer handled the buffering, queuing, and prioritization of data itself. The communications layer APIs were:

Function call	**Parameter(s)**
CommStart	(ErrorNotify)
CommStop	( )
CommCreateAgent	(Agent, SendCompleteNotify, ReceiveNotify, ReceiveCompleteNotify)
CommDestroyAgent	(Agent_number_type)
CommListen	(Listen_Desc)
CommConnect Children	(Agent, ChildDesc, ChildPCI,InterfaceDesc, ParentHint)
CommDisconnect Children	(Connection)
CommSend	(Agent, Buffer_Addr, Size)
CommReceive	( )
CommBufferComplete	(Mailbox)
CommLengthToSize	(Length, Size)
CommGetUserDataPtr	(Agent, Addr)
CommSetUserDataPtr	(Agent, Addr)

In the link layer data were transferred on a byte-by-byte basis over the physical bus between two devices. Link layer API function calls were:

Function call	**Parameter(s)**
LnkStart	(pErrorNotify)
LnkStop	( )
LnkRead	(pLocal, Remote, Len_In_Bytes)
LnkWrite	(Remote, pLocal, Len_In_Bytes)
ErrorNotify	(ErrorNumber)

Upon application of power (power-up), the red and black host processors scanned their respective PCI busses and created memory maps of the location of the available resources. Those memory allocation maps were sent to the control subsystem, which set up static control channels to each of the resources by using the parent–child hierarchical relationship. In order to manage subsystem resources and respond to allocation requests, agents were created. These requests were generated in response to operator commands through the HMI software. Virtual channels were established dynamically by using control messages, which were communicated over the static control-channel structure. Dynamic channels provided direct connection to resources, which were assigned to the channel at the communications layer level, so as to meet the real-time information transfer constraints required.

Via the HMI, the operator initiated system operation and specified how the system would be configured. A menu was employed to facilitate the assignment of the waveform to be used, the radio frequency, and any waveform-specific parameters. Commands were passed onto the control subsystem, which translated these into specific instructions for each of the other subsystems. The subsystems then allocated resources, initialized, and instantiated the channel's waveform application tasks. Instantiation involved: allocating devices, instantiating channel application tasks, creating the connections for the dynamic information paths, setting various waveform-specific parameters, and finally activating the channel.

The five phases of operation were:

- Power Up: Agents, child–parent relationships, and static control channels were established, and BIT functions were performed.
- Instantiation: Communication took place between agents within the protocol stack. Links between agents were 'children' to the broker agent that instantiated the connection. After the child–agents exchanged information, the connection was tested to ensure that the channel was correctly instantiated. Operating software then used these channels to load up the subsystem processors. Agents could deliver messages among the various modules, once the loading was complete.
- Parameters and Mode: Waveform parameters were provided to individual subsystems. Typical parameters included receive/transmit state (the result of a handset's push-to-talk switch), transmit power, and antenna selection.
- Operation: Channels typically transferred information from source to destination through the internal protocol stack. RF channels and network interfaces could be either sources or destinations. They provided the various modes of operation such as: transmit, receive, RF-bridging, and landline switching.
- Teardown: Upon completion of system operation, all agents were deactivated, the channels were disconnected and all the resources were returned to the resource-pool; secondary (persistent) storage was updated and the system was made ready for reactivation.

2.5.3 SPEAKeasy and Link-16

2.5.3.1 Multifunction Information Distribution System (MIDS) [8]

In the early 1960s, each of the Services, independently, initiated the development of tactical data links. In 1974, the then Director Defense Research & Engineering (DDR&E), Dr William Perry, directed that the Services join together to develop a Joint Tactical Information Distribution System (JTIDS). The JTIDS program office was created in 1976. During this time, Dr Perry also offered JTIDS to NATO. By 1987, a NATO STANAG (#4175) had been developed and a few NATO nations began to build terminals in conformance to this MIDS STANAG. Initially, the AF led the US effort, but by 1990 the AF had turned over leadership of the MIDS program to the Navy. In 1991, an international program memorandum of understanding (PMOU) was developed for MIDS and was signed. Supplement 1 to this PMOU (also signed in 1991) placed severe restrictions on member nations and forbade them to develop 'competing systems' to MIDS.

By the early 1990s, the AF had grown concerned about the reliability and cost of the JTIDS and the Class 2 terminals it was developing for installation on small aircraft, i.e. fighters such as F15 and F16. In 1993, the AF initiated the JTIDS Class 2R program, a low-cost variant of JTIDS/MIDS. In 1994, MIDS PMOU Supplement 2 was signed laying out the cost sharing and management structure for an engineering manufacture development (EMD) program. The Defense Acquisition Board (DAB) authorized the Navy to award an EMD contract to MIDSCO – an international consortium of companies made up of GEC–Marconi–Hazeltine (US), Thompson-CSF (France), MID SpA, formerly Italtel (Italy), Siemens (Germany), and ENOSA (Spain). In 1995, to ensure compliance with the MIDS PMOU S-1, OSD directed the AF to terminate their JTIDS Class 2R initiative and join MIDS; the F15 fighter data link (FDL) effort emerged from this.

MIDS had three primary goals. The first was to develop a modular open-terminal architecture that would enable easy integration of the national components/subassemblies onto dissimilar platforms. The MIDS open architecture was based upon commercial standards for real-time processing systems, available commercial components, and the use of a standard electronic module format-E (SEM-E). Open hardware and software standards had not yet been developed when MIDS began. The second goal was to ensure that the MIDS terminal could be affordably tailored to fit a wide variety of military platforms. Lastly, and most importantly, MIDS was to provide an interoperable, jam resistant data link between a multiplicity of diverse US and coalition platforms.

2.5.3.2 SPEAKeasy and MIDS

After SPEAKeasy was briefed to Dr Noel Longuemare, Principal Deputy Under Secretary of Defense (PDUSD) for Acquisition & Technology in April 1996, the SPEAKeasy program gained even more attention. With consideration being given toward implementing Link-16 on SPEAKeasy, and with the DoD's concern over its MIDS PMOU S-1 agreement for non-competing programs, the Deputy Assistant Secretary of Defense (C3I), in a memo on October 1, 1996, chartered a working group to investigate potential cooperation between the MIDS program and the SPEAKeasy program. The task was to identify technology exchange opportunities, identify a potential proof-of-concept demo combining Link-16 and SPEAKeasy, and to further identify areas for potential international participation. A month of intensive meetings involving the AFRL (then Rome Lab), and the offices within CECOM, PM-TRCS, ESC, DARPA, DUSD(I&CP, A&T), OS-JTF, OASD(C3I), and the MIDS PEO/SCS took place in Washington, DC. Architectures, capabilities, functions, configurations, and objectives of the two programs were compared. Technology transfer potentials were examined, with areas for cooperation and technical exchanges identified for both MIDS and SPEAKeasy. Areas for MIDS functional growth (such as beyond-line-of-sight capability, compressed imagery and voice, and multimedia bridging) and warfighter benefit were detailed. The objectives, approach, schedule, cost, and issues for a potential proof-of-concept demo were documented. Issues regarding international participation were enumerated and discussed. A final briefing was given to DASD(C3I) on October 25, 1996. The MIDS EMD schedule, the SPEAKeasy schedule to deliver terminals for TF-XXI, and the accumulated costs associated with the proof-of-concept demo precluded the continuance of this effort and resulted in the loss of a Link-16 capability under the SPEAKeasy program.

2.5.4 Task Force XXI Advanced Warfighter Experiment

Twenty months after contract award, Motorola took two SPEAKeasy ADMs to the Army's National Training Center at Ft Irwin, in the California desert, to participate in the TF-XXI-AWE. TF-XXI-AWE was a 6500-soldier force: 'EXFOR' an experimental force from Ft Hood, Texas, utilizing state-of-the-art systems, against Ft Irwin's 'OPFOR', a Soviet-style force with traditional weaponry. The SPEAKeasy terminals were deployed with the AF TACP and at the Air Operations Center (AOC) to facilitate communications between the US Army and AF CAS aircraft. SPEAKeasy radios were used to communicate in the same manner that current air controllers do with their GRC-206 equipment and also in unique ways never done before. Bridging of voice radio channels was of particular interest to users in the field since it provided the ability for communications to take place directly between dissimilar radios. Bridging enabled tactical air controllers to use their portable VHF-FM radios to speak directly with

F16 pilots who were using their aircrafts' UHF-AM radios. During the exercise, new software was created at Motorola's facility in Scottsdale, Arizona, and downloaded to floppy disks in California, via a telephone modem, and then downloaded directly into SPEAKeasy terminals in the field, adding new communications capabilities to those already available. SPEAKeasy was also repaired in the field with a motherboard stripped from a spare Netis personal computer thus demonstrating the advantages of its 70% COTS implementation.

2.5.4.1 Pivotal Moment for SPEAKeasy

Resulting from the highly successful showing during TF-XXI-AWE, the SPEAKeasy program received a great deal of high-level visibility. DARPA was advocating transition to the Services, and the program as originally scoped was behind in its long-term design for wideband operation and over budget. The AF decided that it was more important to push for an acquisition program to field capability styled along the lines of SPEAKeasy architecture and capability than to invest more research funds in an R&D program. SPEAKeasy tasks to lower technical risk and demonstrate wideband waveforms, networking, and reprogrammable cryptology had been postponed due to the focus on TF-XXI. The OSD had already initiated the Programmable Modular Communications System (PMCS) Integrated Product Team (IPT), which is discussed later in this chapter, a month before TF-XXI, and the Services were now eager to move ahead to acquire the capability demonstrated by SPEAKeasy. The decision to withhold funding for the SPEAKeasy effort signaled the effective end of this R&D program.

2.5.5 Achievements of SPEAKeasy

The open system design, the use of 70% COTS, the reprogrammable nature, and the ability to bridge between disparate systems were the indisputable strengths of SPEAKeasy. At the time, there were a number of implementation weaknesses identified. The use of the homodyne approach was perceived as the potential limiting factor (risk) in the implementation of wideband waveforms. As it was, SPEAKeasy Model 1 terminals were limited to 4–400 MHz in operation, the planned enhanced RF modules, 2 MHz–2 GHz, were never integrated or tested. The PCI bus, with PCMCIA card utilization, was limited to only a few module slots. It became necessary to install bridge chips to extend the PCI busses to accommodate the number of cards required. The bridge-chips themselves had additional limitations and a work-around in the message-passing scheme became necessary to reduce latency and eliminate non-deterministic behavior.

Originally, SPEAKeasy Phase II was to implement the CYPRIS-based INFOSEC design, which Motorola had developed during Phase I. Motorola, under IR&D funds was pursuing an alternative approach since they felt that the CYPRIS INFOSEC module would not be adequate for the wider band waveforms. They were working on their programmable advanced INFOSEC module (AIM) consisting of three distinct 32-bit RISC machines with 100 MHz clocking which projected 1200 MIPS in a 3 V package.

SPEAKeasy had received significant attention by the mid-1990s that the SPEAKeasy program was inundated with requests for information as to whether SPEAKeasy terminals could support such and such waveform or be integrated on such and such a platform. Motorola provided various white papers and supplied rough-order-of-magnitude (ROM) cost figures projecting the potential R&D or production costs as requested. The AF was interested in a SDR if it was capable of transmitting and receiving Link-16. Link-16 was the only ‘new’ communications requirement yet to be satisfied for many of their aircraft. TACP equipment was in need of an upgrade and therefore the bridging capability of a terminal like SPEAKeasy was also attractive.

White papers for both a four-channel TACP MBMMR and optional Link-16 compatible JTIDS waveform development, utilizing the SPEAKeasy architecture and technology, were authored in January 1996. The TACP terminal was projected to be significantly smaller (size, weight, and power) than the existing, rather large, GRC-206 terminal suite. It would provide redundancy, since each channel could be reprogrammed as necessary, it would also provide bridging between diverse radios and have future-proof capability with its ability to add new waveforms in the field.

The Link-16 white paper described how Motorola, with their teammate Lockheed-Sanders, proposed to take the product of the Sanders JTIDS Class 2R affordability manufacturability technology demonstration (AMTD) program and implement Link-16 in a SPEAKeasy Phase II terminal. The SPEAKeasy functional architecture paralleled that of the Sanders JTIDS AMTD architecture. The software and FPGAs developed for the Sanders’ JTIDS AMTD program, were projected to be portable at minimal nonrecurring cost and without any changes in the digital architecture of the radio. The SPEAKeasy modem processing capability (at the time estimated at over 34 GOPS, at chip rates up to 25 Mcps) was seen as exceeding what was needed to process the Link-16 waveform. The proposed implementation used two antennas with one SPEAKeasy channel dedicated to each antenna. SPEAKeasy would monitor two of the possible RF frequencies for acquisition. After acquisition, SPEAKeasy would tune to the subsequent frequencies for receive and transmit using the same two T/R modules in a ping-pong manner thereby reducing the tuning time requirements for a T/R module. The antenna interface hardware developed for AMTD was planned to be used with minor modifications constituting a straightforward appliqué to the radio’s external RF. A full technical report on JTIDS operation for the SPEAKeasy Phase II MBMMR was delivered under the contract in August 1997.

Just as in Phase I, SPEAKeasy Phase II did NOT develop, did not implement, and did not demonstrate any wideband capability. Wideband waveforms such as EPLRS, Link-16, and the VRC-99, although studied, were never implemented. Also, four-channel operation, data-gateways (between diverse wideband data waveforms), and internetworking capability were never implemented under SPEAKeasy. These were all objectives that were not met due to insufficient funds and the early conclusion of the R&D program.

2.6 Programmable Modular Communications System (PMCS)

There were many USD (A&T) initiatives to encourage the implementation of open system designs to attain their full benefit. MIDS milestone-II DAB had directed the redesign to incorporate open system design features. The Link-16 FDL program was directed to employ the MIDS open system design. Discussions under the MIDS/SPEAKeasy cooperation working group, and the tactical common data link (TCDL) open system architecture working group, all set the stage for a new USD (A&T) initiative. The Quadrennial Review and a number of Congressional bodies had identified that there were more than 200 separate DoD radio programs. In February 1997, under the direction of OSD(C3I), a PMCS-IPT was established to identify a PMCS open system architecture, incorporating all functions required to transmit, receive, and interface to host platforms, and develop a migration strategy from legacy systems to PMCS. The objectives were to:

- attain the cost-effective acquisition of the next generation of communications systems based on open system design standards;
- maximize the use of available commercial hardware and software to reduce both recurring and non-recurring costs;
- minimize proprietary solutions and maximize use of commercial standards to increase the number of potential equipment providers;
- minimize the number of discrete and unique hardware suites and maximize software reprogrammability and commonality in order to expand the production base.

The PMCS-IPT was headed by ODASD(C3) director of communications, and pulled in membership from BMDO, DARPA, DARO, DISA, USA, USN, USMC, USAF, the Joint Staff, NSA, and the FAA; all of the Service labs were involved. Status was periodically briefed to DASD (C3), DASD (C3IA), ASD (C3), and USD (A&T), and the working groups efforts amounted to an aggressive 4-month effort reviewing prior and ongoing Service/Agency programs and accomplishments. The PMCS-IPT strove to identify common areas of agreement, differences in implementation approaches and their rationale, and recommend a high-level architecture along with the critical interfaces that must be specified and controlled. Security and programmable INFOSEC device maturity were significant areas of concern and attention. Service and Joint programs such as SPEAKeasy, MIDS, joint combat information terminal (JCIT), and the FAA's planned next-generation communications efforts were briefed and discussed in great detail.

2.6.1 The PMCS Architecture [9]

There are two diagrams that are most useful in understanding the PMCS. The first is the entity reference model (ERM, Figure 2.14) and the second is the software reference model (SwRM, Figure 2.15).

Referring to Figure 2.14, the PMCS ERM was very similar to SPEAKeasy's functional allocation (Figure 2.12). The ERM contained eight functional entities where each was to carry out a specified set of communications capabilities or functions. Not every functional entity would be necessary for every user. The ERM represented the first level allocation of PMCS functions that were required to satisfy the broad range of capabilities and services that government users needed and expected from an advanced communications architecture. The critical system interconnect (CSI) functional entity was the split Black and Red interconnects required to achieve NSA endorsement. In some applications information would be protected (encrypted) at its origin and would thus not require additional transmission protection. In yet other cases, communications would always be 'in the clear' and there would not be a need for an INFOSEC functional entity. The ERM illustrated that it was intended to support multiple simultaneous communications channels. The ERM was not intended to specify particular packaging or implementation; it was meant to help achieve the PMCS attributes of scalability, extendibility, and affordability. A functional entity could consist of one or more hardware or software modules. Entities that were satisfied in software could have coexisted on a single hardware module and would have been initialized with software for the various communications functions required.

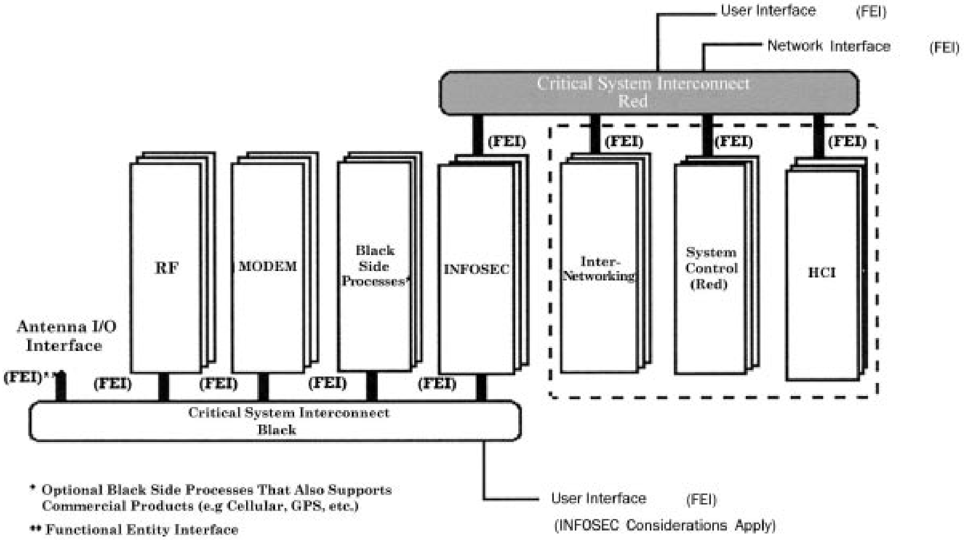

Figure 2.14 PMCS entity reference model

The SwRM (see Figure 2.15) identifies key attributes: software independence from the underlying hardware, the independence of all application software, and that common software services were shared among various software applications. This was achieved by standardizing the direct interfaces between the layers. The figure was not meant to imply that a common operating system (OS) was to be used throughout the system. Appropriate APIs and external environment (i.e. physical and electrical) interfaces (EEIs) isolated the applications and the OS and permitted distributed processing and different operating systems to be used on different entities. For an expanded view of the interfaces and their definitions refer to Figure 2.16.

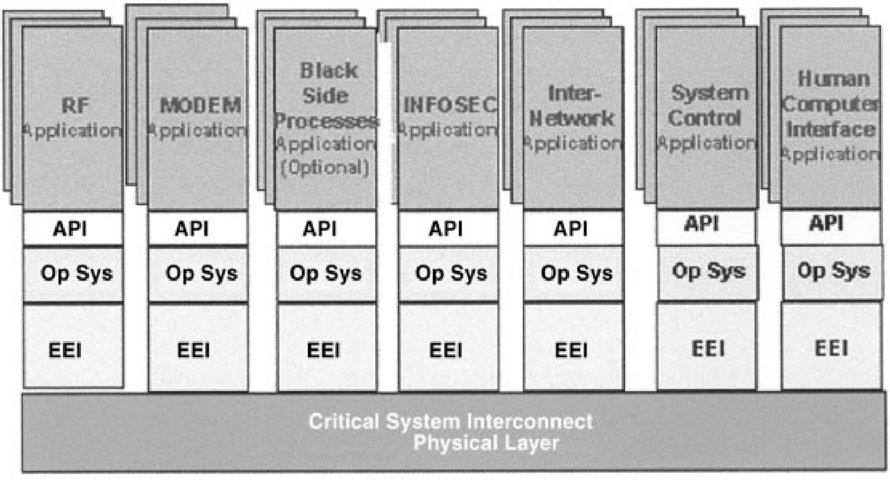

Figure 2.15 PMCS software reference model

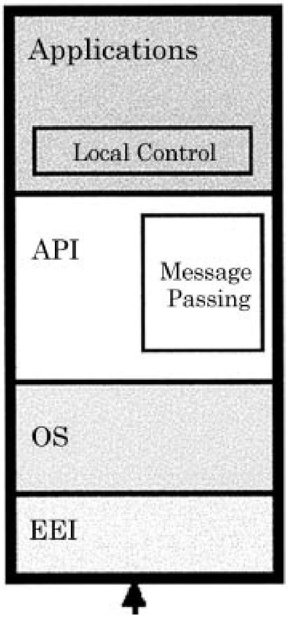

Figure 2.16 PMCS critical interfaces – expanded view. Applications: These are the software programs specific to a functional entity; Local Control: This subfunction provides a common control interface for interacting with System Control, and manages intra-entity applications; Application Program Interface (API): This is a common set of calls that provides a level of abstraction between the application and the operating system or other services to ensure portability of the application code; Message Passing: This critical subset of the API defines the calling conventions for intercommunication among entities; Operating System (OS): This manages the processes, files, and resources within the functional entity. These OS functions could be provided by COTS, or "home-grown". The OS does not have to be common across entities; External Environment Interface (EEI): This provides reliable delivery of messages between entities connected to the common.

The results of the PMCS effort was published on July 31, 1997, and are available on the World Wide Web [9].

2.6.2 The Migration of PMCS

In July 1997, the activities of the PMCS-IPT and the resulting Guidance Document were briefed to the USD (A&T). In a letter dated July 28, 1997, then Acting Director USD (A&T), Mr Anthony Valletta, stated the PMCS concept for future acquisition had been accepted. He directed that a working group from the PMCS-IPT be established to further refine the PMCS and identify acquisition management options for a joint service program. The Acquisition Management Working Group (AMWG) was chartered to complete its efforts within 30 days, and was led by the Director of Communications, Mr Richard Dyson. The Joint Requirements Oversight Council (JROC) had validated a Joint Tactical Radio Mission Need Statement (MNS) earlier in August.

In a decision memorandum dated September 11, 1997, then Acting USD (A&T), Mr R. Noel Longuemare established the PMCS as a major defense acquisition program (MDAP) with the Army as the permanent component acquisition executive and lead service for the PMCS. The AF was directed to assign an initial program manager (PM) to lead a Joint Program Office (JPO). Service PMs were directed to serve in a rotating manner, and deputy-PMs were to be assigned for each of the Services. PMCS was placed under the oversight of a C3I-Systems Overarching IPT (OIPT). The JPO was given responsibility for budgeting and executing RDT&E funding, maintaining the PMCS open architecture, and for procuring common software and hardware modules. The JPO was directed to ensure that the maximum number of industrial firms participated in each phase of the evolutionary development of a PMCS family of radios. The JPO was established as the JTRS JPO after the title of the MNS and draft Operations Requirement Document (ORD).

In April 1998, PDUSD (A&T), Jacques S. Gansler, sent a letter to all the Service Acquisition Executives stating that he was concerned with Service plans to proceed with near-term radio and terminal developments, thus continuing to field legacy systems. He directed that each Service Acquisition Executive take whatever steps necessary to minimize new programs and migrate existing development programs to the target single acquisition program, JTRS. Later that year, in the end of August 1998, ASD (C3I), Mr Arthur L. Money, concerned that the Services were not aggressively following Mr Gansler's direction, followed up with another memorandum to all the Service Acquisition Executives. He wanted to preclude efforts from independently developing and acquiring service unique radios and directed that all current Service "… efforts to initiate any contracting activity to develop and acquire any radio system to include software programmable radio technology are to be held in abeyance". No Broad Area Announcements and no Requests for Proposals were to be released without his direct approval. Any requests for 'waivers' were to be submitted through, and reviewed by, the JTRS JPO. Hence, the Services were then locked into supporting the JTRS initiative if they wanted any new communications capabilities, and the JTRS JPO was fully established.

2.7 Other DoD SDR Programs

2.7.1 Joint Combat Information Terminal (JCIT) [10]

There is a long history of how the Naval Research Laboratory's (NRL) Navy Center for Space Technology got into the business of developing communications equipment. NRL placed transponders in the multi-spacecraft dispenser, the upper stage vehicle that inserted payloads into orbit, so as to provide near real-time reports. From this effort grew the tactical receive equipment (TRE) and eventually a flight box, the multi-mission advanced tactical terminal (MATT), capable of simultaneously receiving and processing intelligence reports for tactical receive applications (TRAP), tactical data information exchange system broadcast (TADIXS-B), and tactical information broadcast service (TIBS). A number of MATT-like devices had been made for Special Forces. The Army had a requirement to build an Army aviation command and control system (A2C2S), which required dozens of discrete radios to meet worst-case scenarios. The development of a multi-channel system to adapt to meet various communications needs led NRL, leveraging their efforts under MATT, the improved data modem (IDM passes digital data for targeting or situation awareness) and the

Commander's situation awareness workstation (CWAS), to initiate development of the enhanced communications interface terminal (ECIT) in 1993. ECIT had five multiband receivers and covered HF, VHF, and UHF. It employed a number of programmable modules and its transceivers supported multiple waveforms, ECCM, and FEC techniques. ECIT (used on the UH60C helicopter) evolved into an eight-channel system that was capable of covering 2–512 MHz, and expandable to 2.5 GHz, and is now known as the joint combat information terminal (JCIT).

The JCIT configuration is shown in Figure 2.17 and its architecture in Figure 2.18.

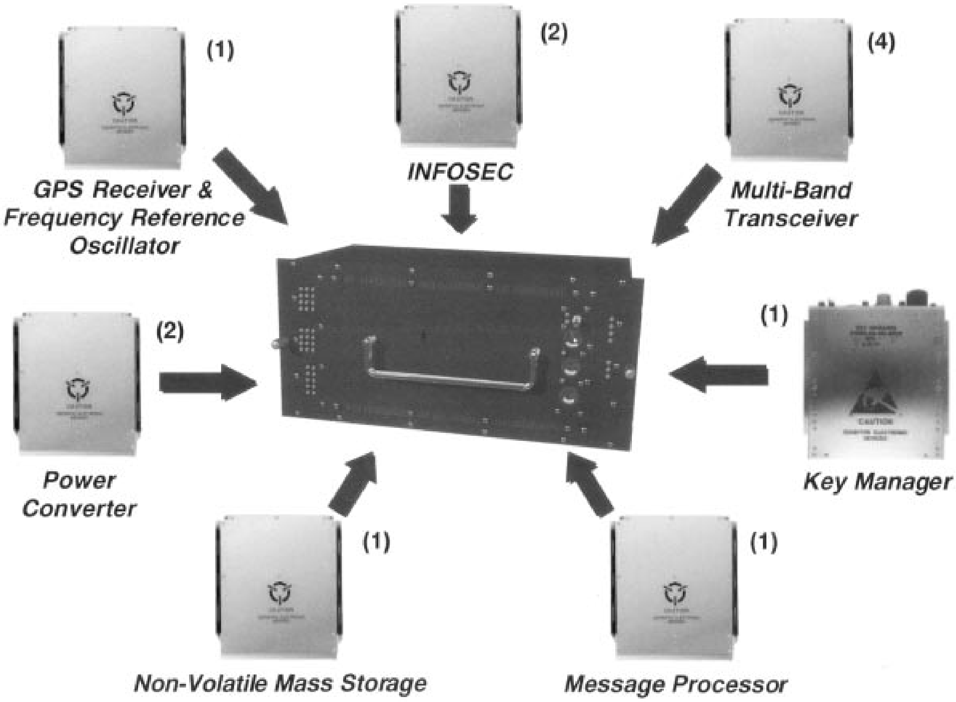

Figure 2.17 JCIT configuration

JCIT was configured using SEM-E modules and an IEEE 1394 backplane. JCIT has an open system hardware and software architecture developed under NRL and is owned by the government. JCIT implements many modulation formats (AM, FM, SSB, BPSK, SBPSK, QPSK, SQPSK, SOQPSK, MSK, CPFSK, DSSS, FH, GPS, CDMA, TDMA), and many protocols (ATM, TRAP, TADIXS-B, AFAPD, TACFIRE, TIBS, JTIDS, TRIXS, TADIL-A/B/J). The system is software reprogrammable to support a variety of mission scenarios and is portable operating system interface (POSIX) compliant, uses VxWorks, and its software is coded using both Ada and C. The JTRS program has leveraged much of the software structure used in the JCIT effort.

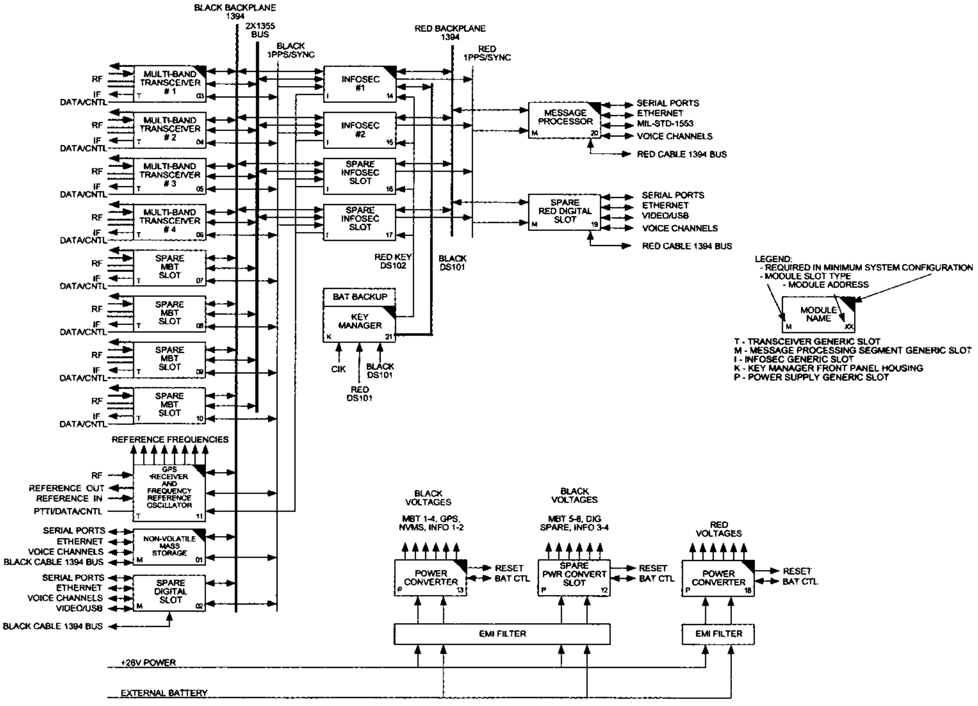

Figure 2.18 JCIT architecture

2.7.2 Global Mobile (GloMo) [11]

DARPA's GloMo program had the vision to "Develop and integrate technologies and techniques at applications, networking and wireless link levels that will enable wireless users to access and utilize the full range of services available in the Defense Information Infrastructure." The GloMo program addressed mobile application support techniques, mobile networking, and wireless nodes and was comprised of more than two-dozen efforts by industry and academia. Only a few are summarized below.

2.7.2.1 Wireless Internet Gateways for Internets (WINGs) and Secure Protocols for Adaptive, Robust, Reliable, and Opportunistic WINGs (SPARROW)

The University of California, Santa Cruz, developed and analyzed packet-radio networking protocols and architectures that would provide guaranteed service for multimedia traffic and to provide a seamless extension of the Internet. They used and improved the C++ protocol toolkit (CPT). Packet radio prototypes were used to test and demonstrate results using modular, high-speed, low-cost, commercial, spread spectrum radio hardware. Under SPARROW, secure protocols were designed for exchanging control information to protect nodes against compromise. The WINGs protocols were leveraged by a number of other DoD programs.

2.7.2.2. Advanced Signal Processing & Networking (ASPEN)

The prime objective of the ASPEN project was to enhance packet radio networking protocols using digital programmable radio technology in order to demonstrate quality of service networking. ASPEN utilized the WINGS protocol and focused on enhanced throughput, a wideband waveform with Doppler tracking, and variable processing gain.

The program's objectives were to:

- demonstrate an advanced wireless network, link protocols, programmable multi-channel wideband radios, including enhanced throughput, utilizing GloMo radio APIs and a wideband waveform (with Doppler tracking and variable processing gain);
- investigate and demonstrate adaptive signal processing techniques;
- develop tactical Internet traffic models and demonstrate a wireless network using ASPEN radios.

2.7.3 Ultracomm

Ultracomm was a DARPA effort that was targeted toward reducing the footprint of a SDR by employing size reducing technologies such as: silicon carbide amplifiers and microelectromechanical-system (MEMS) devices and filters.

Raytheon E-Systems of Falls Church, Virginia was awarded a contract to develop a multiband, multimode communications system based on a family of modular components, packaged in the widely used PC card format (PCMCIA). One Ultracomm system provided four independent communication channels, with each channel capable of covering the RF communication bands between 20 MHz and 2.8 GHz. The system had a wide 60 MHz instantaneous bandwidth, was low power, and was completely software reconfigurable throughout the spectrum. It accomplished this via MEMS filtering, which provided highly integrated preselection across the entire spectrum on a single silicon chip. Silicon germanium ASICs were used to produce a high performance RF analog signal processor that could be closely integrated with the MEMS filter devices. State-of-the-art analog-to-digital converters were used to achieve an impressive instantaneous bandwidth and allow much of the signal processing to be done using inexpensive digital components. Silicon carbide power microwave devices were used to develop a high power density amplifier for the transmitter. Power MEMS devices provided for efficient power transfer by exactly matching impedance across the entire spectrum. All of the technologies were integrated together using advanced packaging techniques, high-density multi-chip modules, and optical interconnects.

2.7.4 Wideband Radio Networking (WRN) Program[3]

As indicated earlier, the US Army Communications & Electronics Command (CECOM) at Fort Monmouth, New Jersey, was an original member of the Joint SPEAKeasy Multiband Multimode Radio (MBMMR) Program, along with the US Air Force and DARPA. A SPEAKeasy objective of major interest to the Army was the program goal to evolve and

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[3] This section was authored and provided by Mr Donald W. Upmal, WRN Project Leader, US Army Communications & Electronics Command, Fort Monmouth, New Jersey.

enhance the engineering prototype radios over the 4-year program period to support not only narrowband low data rate waveforms, but also to support wideband high data rate waveforms. The Army's special interest in this capability was driven by their extensive modernization plans and future vision to 'digitize the battlefield' of the twenty-first century. Lessons learned during the Task Force XXI tactical field exercises in March 1997 further emphasized the Army's urgent need to develop new higher data rate waveforms to supplement the low data capacity of today's legacy radios, such as the SINCGARS, EPLRS, and NTDR radios. This same need was later reflected in the Operational Requirements Document for the JTRS, specifying the requirement to develop a new wideband networking waveform for the future JTRS family of radios. When the SPEAKeasy program was restructured in 1997, due to the lack of required additional funding after TF-XXI-AWE, all the development tasks related to wideband capability were eliminated. Subsequently, the Army decided to shift its FY98–99 funds to an effort that would better support their need to develop high data rate wideband waveforms. Thus, the Army WRN program was born.

In November 1997, CECOM issued a broad agency announcement (BAA) entitled Wideband Radio Networking, with the program objective to provide an enhanced experimental capability within the CECOM Research, Development & Engineering Center (RDEC) to facilitate the development and evaluation of new wideband radio network waveforms and technology. The BAA solicited the development and delivery of four products:

- a modular software based programmable wideband network radio (WNR);
- a computer automated wideband radio network testbed (WRNT);
- a wideband WNR test waveform; and
- a software development environment for the WNR.

The WNR was to be used to host new candidate wideband waveforms and, along with the WRNT, provide the CECOM RDEC with an enhanced network radio testbed capability to develop and experiment with third party/industry network waveforms, adaptive protocols, and radios, as well as provide a testbed for candidate JTRS waveforms and DARPA program networking technology. The WRN contract was awarded in April 1998 to prime contractor Raytheon Company, Fort Wayne, Indiana, requiring the delivery of three WNR radios.

The contract specified that the WNR architecture be mainly software based and reprogrammable so that performance and functional improvements could be upgraded and controlled through software only, with minimal hardware changes. With the intent to leverage as much currently developed software radio technology as possible, the contract also required the WNR architecture conform to the latest PMCS reference model to the greatest extent possible, and that the 'radio APIs' developed under the DARPA GloMo program be used during software development. To reduce cost, it was also required that the design be COTS/NDI based to the maximum extent feasible. The final Raytheon design produced the radio shown in Figure 2.19, having an open hardware architecture using a standard COTS 19" rack chassis and dual 3U compact PCI (cPCI) card cages, with standard cPCI data busses, control processor (CPU) cards, and Ethernet I/O cards.

As shown in Figures. 2.20 and 2.21, the open modular architecture conformed exactly to the top level PMCS reference model, including separate Red and Black data busses, allowing implementation of secure INFOSEC features and operation during future upgrades. Due to contract schedule constraints, the programmable INFOSEC module design was not completed prior to WNR delivery, therefore a standard Ethernet interface

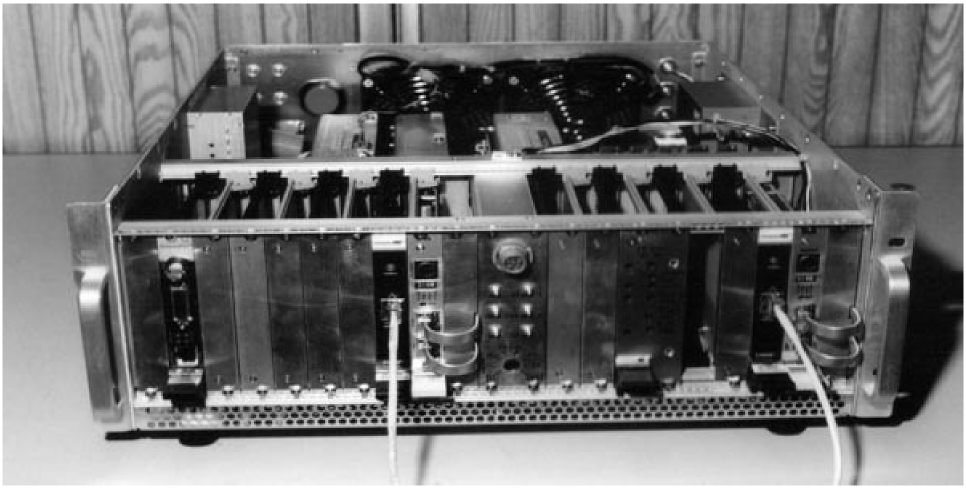
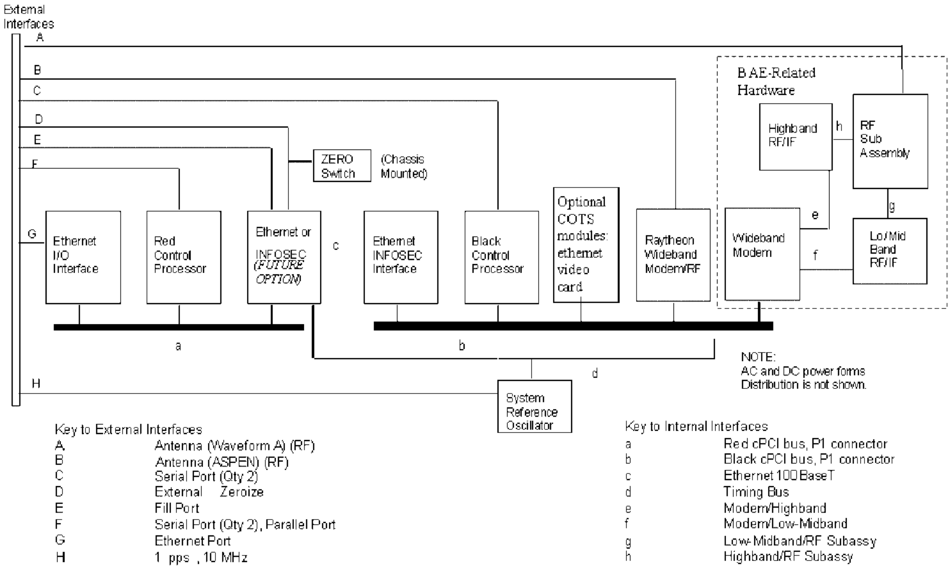


Figure 2.19 Army wideband network radio (WNR)

was used as an interim gateway between the Red and Black data busses. As a result of the flexible hardware and software design and numerous spare card slots, the WNR design could support multi-channel operation (as illustrated in Figures. 2.20 and 2.21), but the WRN contract only required the single ‘Raytheon wideband modem/RF’ channel be implemented and delivered.



Key to External Interfaces

A	Antenna (Waveform A) (RF)
B	Antenna (ASPEN) (RF)
C	Serial Port (Qty 2)
D	External Zeroize
E	Fill Port
F	Serial Port (Qty 2), Parallel Port
G	Ethernet Port
H	1 pps , 10 MHz

Key to Internal Interfaces

a	Red cPCI bus, P1 connector
b	Black cPCI bus, P1 connector
c	Ethernet 100BaseT
d	Timing Bus
e	Modem/Highband
f	Modem/Low-Midband
g	Low-Midband/RF Subassy
h	Highband/RF Subassy

Figure 2.20 WNR block diagram

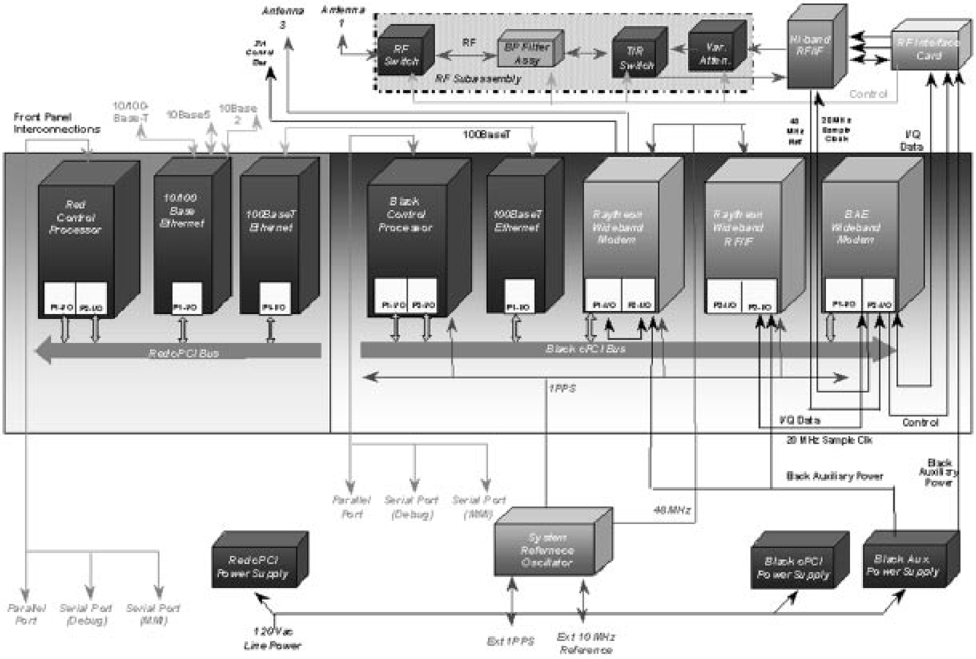


Figure 2.21 WNR open modular architecture

The WNR could be controlled by any standard PC HMI running the host network manager (HNM) software and connected to the COTS 'Ethernet I/O interface' card plugged into the red side cPCI bus. The HNM software provided simple GUI screens and menus, and allowed easy user control of all radio system and waveform functions and features.

The majority of the radio system control, bus control, networking, and high-level waveform functions were performed in (and divided between) the Red and Black control processors. The two COTS PEP modular computers CP-310 processor cards were identical and include a 166 MHz Pentium processor, 64 Mbytes DRAM, 80 Mbytes flash ROM, full complement of serial and parallel ports, and a cPCI bus interface. All system and waveform executable software, which resides on the control processors, were downloaded and/or reprogrammed directly from the HMI PC via the Ethernet I/O and cPCI bus interfaces.

The wideband (WB) modem card and RF front end circuit card were two custom Raytheon designs, and were sandwiched together to form a double-width cPCI 3U module. Again, to leverage current technology and reduce cost, the WB modem/RF module design was a previous Raytheon development under the DARPA ASPEN radio program and re-used on the WRN program.

The programmable elements of the WB modem included a Texas Instruments TMS320C548 DSP and two dense Xilinx XC4085XL FPGAs. A Qualcomm Q1900 Viterbi decoder and DA/AD converters were also located on the card. This combination of baseband processor elements performed all the data modulator/demodulator functions necessary to process a wide variety of digitally modulated waveforms. All modem and waveform related executable software, which resided on the DSP or FPGAs, was downloaded and/or reprogrammed via a JTAG connector located on the edge of the WB modem card by simply lifting the WNR top cover.

The RF front end card provided all the required receiver/exciter functions in two selectable frequency bands; 225–500 MHz (lowband) and 500–1000 MHz (midband). The maximum RF output was nominally −3 dBm, with 20 dB of output power control (attenuation) in 1 dB increments. An internal R/T switch provided a single RF interface to an external antenna port. When needed, RF power amplification was provided by an external power amplifier. A highband 1.3–2 GHz RF module was also developed under the WRN contract, but was not fully implemented in the delivered radios.

At the time of the WRN contract award, Raytheon had already been an active member of the SDR Forum and was preparing their technical proposal for JTRS. Raytheon used a consistent software approach for all three efforts, the WNR architecture design and implementation was a stepping stone (with lessons learned) toward the development of the JTRS architecture. The WNR software architecture therefore was an early version of today's JTRS architecture and its basic structure is shown in Figure 2.22.

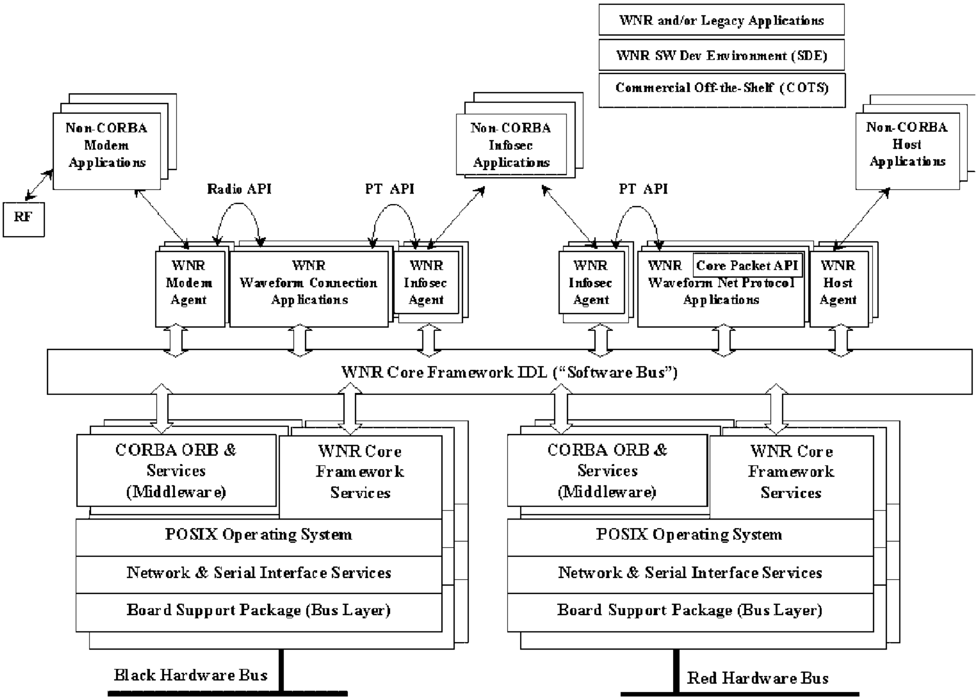
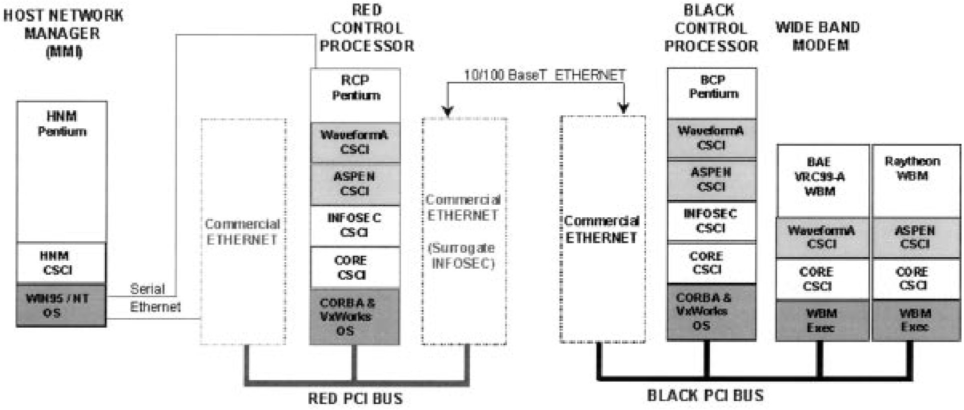


Figure 2.22 WNR open software architecture

From top to bottom, this layered architecture consisted: of an application layer, where the major radio/waveform functional software resided; a core framework layer, which provided an essential set of open application-layer interfaces and services; a common object request broker architecture (CORBA) layer, which was standard commercially available 'middleware' facilitating message passing and a distributed processing environment; a POSIX OS layer, where commercial VxWorks OS software resided; a network & serial I/O services layer, where commercial components provided these functions and protocols; and a board/bus layer, where the standard cPCI software resided for the WNR.

The WNR software uses a distributed control structure in support of the object-oriented design. Therefore, as mentioned earlier, computer software configuration items (CSCIs) were distributed across several processors within the WNR system. This distribution is shown in Figure 2.23, with the four major WNR CSCIs being the core CSCI, INFOSEC CSCI, HNM CSCI, and ASPEN waveform CSCI. The fifth waveform-A CSCI shown in the figure was for an additional WNR waveform, but was not completely implemented in the delivered WNRs.



PROCESSOR BOARD	PORTABLE CSCIs	NON-PORTABLE CSCIs
VRC99A WB Modem		INFOSEC, Core, WaveformA
Raytheon WB Modem		INFOSEC, Core, ASPEN
Black Control Processor	WaveformA, ASPEN	INFOSEC, Core
Red Control Processor	WaveformA, ASPEN	INFOSEC, Core
Host Network Manager		Host Network Manager

Figure 2.23 WNR software distribution

The WNR software architecture provided isolation and standard interfaces between the underlying software and hardware layers and the upper level application layer software, assuring enhanced portability, reconfigurability, and interoperability of software and hardware components developed using this architecture. It also provided a building-block structure for defining APIs between application software components.

The ASPEN waveform implemented on the WNR was also a re-used product from Raytheon's previous DARPA ASPEN program and had a two-fold purpose:

- provide a test waveform robust enough to sufficiently stress the WNR to assure its final design could host future experimental wideband waveforms and associated adaptive networking features;
- be evaluated as a candidate JTRS network waveform.

The ASPEN physical layer modem/signal-in-space was a quasi band limited (QBL) DSSS waveform, using DPSK data modulation, convolutional FEC coding, and block interleaving. It used a 20 Mcps chip rate, with individually selectable spreading ratios and packet lengths.

During WNR acceptance testing the ASPEN waveform, with its very robust RF characteristics and adaptive networking features, was found more than adequate as a test waveform. At the time of this writing, the WNRs were being used by US Army CECOM to implement and test additional wideband waveforms as possible candidates to meet the Army's future JTRS operational requirements.

2.8 Ongoing US Initiatives

2.8.1 Joint Tactical Radio System (JTRS)

The JTRS program, as previously mentioned, was established as an outgrowth of OSD's PMCS effort. The ORD requirements for scalability, portability of waveforms, and extensibility drive the need for a common software communications architecture (SCA). To develop an appropriate common, open architecture, which would satisfy current and future military requirements, the JTRS JPO divided the program into a number of 'steps' or phases. Step 1 dealt with architecture framework, Step 2 with architecture development, and Step 3 will develop waveform software to satisfy the common Service requirements as specified in the JTR Joint ORD.

2.8.1.1 Step 1

Via an open competition, the JTRS JPO arranged for three industry consortia to construct preliminary architectures. The three consortia included a total of 30 companies (and universities). Boeing, Motorola, and Raytheon led Step 1 initiatives, respectively.

The emphasis of Step 1 was on determining the appropriate level of specificity within the architecture. The questions were where to draw the line between standardization and vendor implementation, see Figure 2.24, and what would be the modular granularity required?

The industry consortia was considered an essential in that no one company had all the expertise to pull off this development alone, and it was necessary to ensure adequate buy-in for the SCA to have any hope of becoming a true industry standard. Each consortium developed a framework and a rough baseline. From these three preliminary architectures, the JPO selected one as the foundation to build upon. The government developed an architecture definition report to serve as a guideline for further development and to identify important features to fold into the 'best of breed' from all the other consortia. These formed a baseline framework from which SCA development could proceed.

2.8.1.2 Step 2A

The baseline framework developed during the first step provided the foundation for the SCA. However, further detail was required to develop a full architecture that could be used for the production of Service radios. Greater detail and specificity, complete interface descriptions, and various performance issues needed to be resolved in order to develop a viable architecture that would satisfy the JTRS Statement of Objectives (SOO) and the requirements of the ORD. The JTRS JPO competitively awarded a single industry consortium with responsibility for further SCA development. The winning consortium was comprised of Raytheon Systems Company, ITT Aerospace Communications Division, Rockwell Collins, and Marconi Aerospace System, Inc., the CNI Division (now BAE Systems).

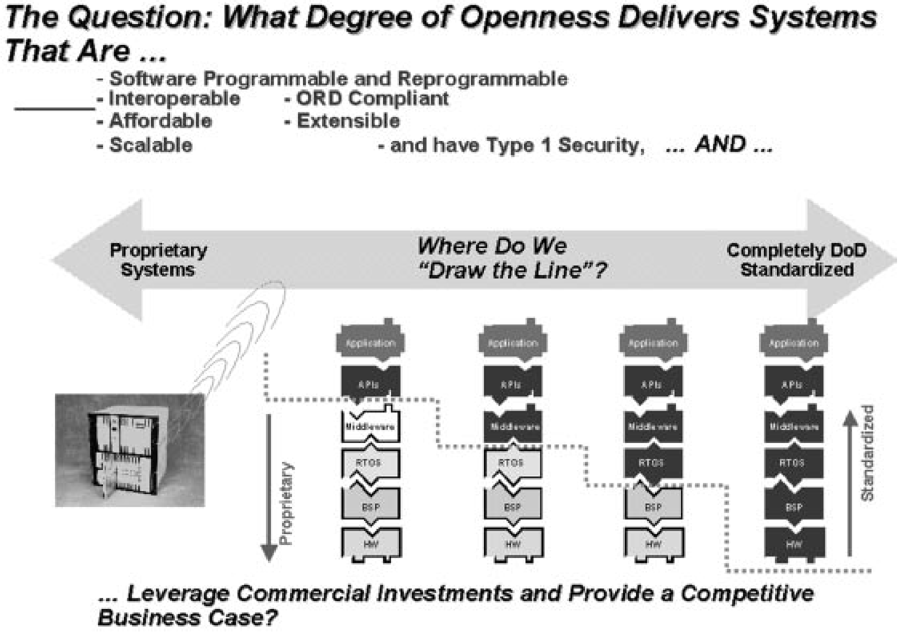


Figure 2.24 JTRS architecture: the bottom line

Under the agreement, the consortium developed and validated the SCA, which, as of May 2001, is a specified set of rules, methods, and design criteria for implementing software reprogrammable digital radios, see Figures. 2.25–2.27. The Operational Environment Overview, Figure 2.25, identifies critical interfaces and the boundaries where control is needed.

The software structure diagram, Figure 2.26, shows the application modules, their interconnection and APIs to the core framework (CF) and the CORBA middleware. Three major elements of the SCA are a real-time operating system (RTOS), a real-time object request broker (ORB), and a CF. Object management group (OMG) interface definition language (IDL) specifies the interfaces between system software components while the extensible markup language (XML) is used to identify and define capabilities, dependencies, and the location of ‘resources’ available (hardware and software modules) in the system.

The CF IDL relationship chart, Figure 2.27, displays inheritances and interconnections.

The consortia’s members each played a part in validation of the implementation-independent SCA by developing unique, functionally compatible and interoperable prototypes:

- Raytheon’s validation demo model (VDM) was a four-channel prototype that had two half-duplex wideband (225 MHz–1 GHz) and two narrowband (100 kHz–2 GHz) channels. It was configured in a 19-inch chassis having a combination of 3U and 6U boards on a cPCI bus. The VDM was to have VHF (AM, FM, and ATC-8.33 kHz), UHF Have Quick I/II, DAMA/DASA (181A, 182A, 183A 25 kHz and 5 kHz-voice), and the ASPEN wideband waveform. Raytheon expected to host ported waveforms from Rockwell, ITT, and BAE.

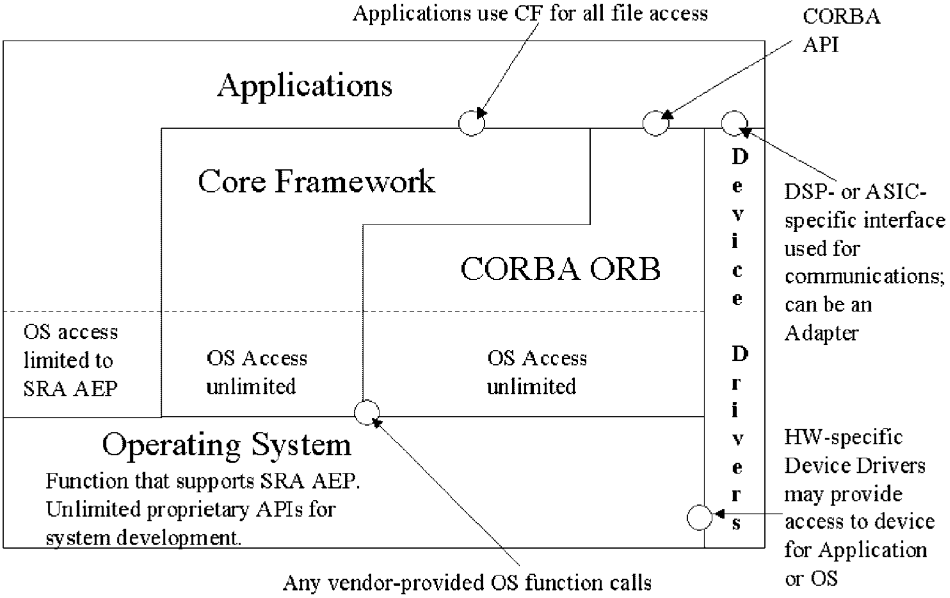


Figure 2.25 SCA operational environment overview

- Rockwell built a 19-inch rack mounted (6 ft) SEM-E, 3U prototype. It employed a VME-bus and had four channels (2 MHz–2 GHz), external INFOSEC (4 KY-100s), PowerPC with LynxOS and CORBA ORBexpress. They invoked HF-SSB, HF-ALE, and VHF-FM.
- ITT had a two-channel prototype that used a PC/104-Plus bus architecture, 30–450 MHz RF, and transmitted and received selected modes of SINCGARS ASIP/INC.

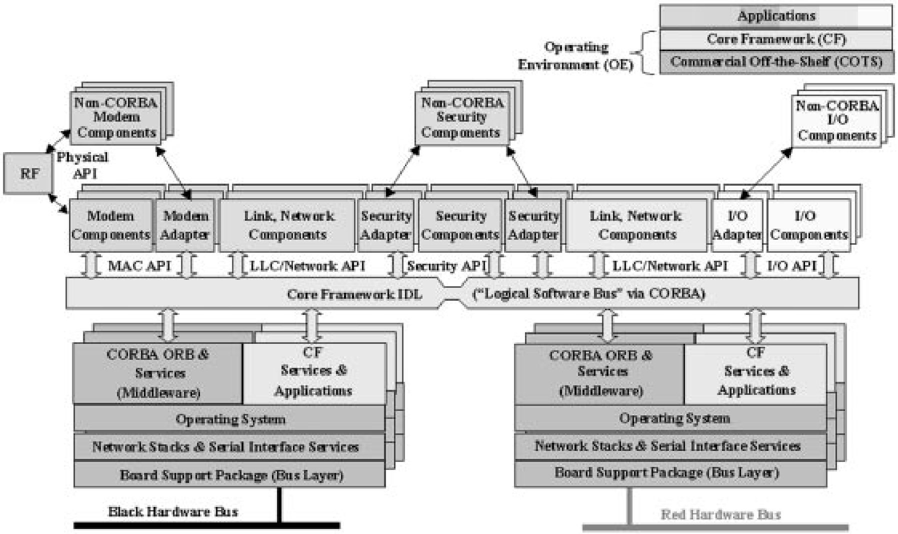


Figure 2.26 SCA software structure

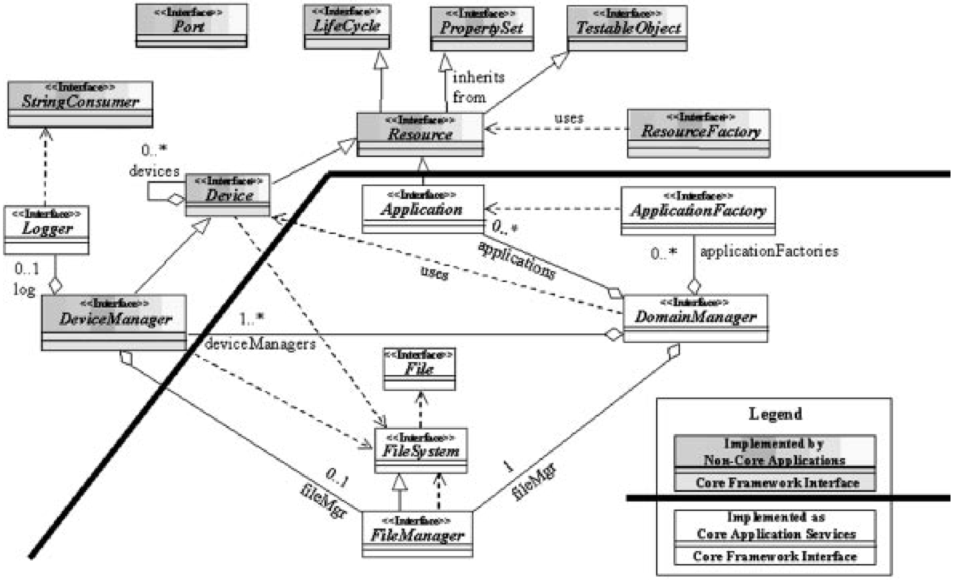


Figure 2.27 Core framework IDL relationships

- BAE's maritime prototype had a cPCI configuration with a 6U card cage, four channels with operation in HF, VHF, and UHF, discrete INFOSEC, and transmitted and received their proprietary AN/VRC-99 waveform.

SCA validation was accomplished by analysis, test, and demonstration.

2.8.1.3 Step 2B

In order to fully achieve the Step 2 goal of successfully developing, testing, and validating the emerging SCA, the JTRS JPO wanted third parties to work in parallel with the Step 2A consortium. Step 2B efforts would assist in the development, test, and validation of the emerging SCA by the use of SCA compliant software or hardware prototyping activities. Both Steps 2A and 2B proposed to include porting demonstrations between prototypes. The JTRS JPO awarded Step 2B efforts to Motorola; Boeing; Rockwell Collins; Harris RF; RACAL; and Vanu Inc.

- Motorola was awarded a 2B effort to demonstrate that their wireless information transfer system (WITS) was in compliance with the JTRS SCA. Motorola was to demonstrate their WITS radio operating commercial waveforms (AM and FM) while utilizing the software application interface descriptions defined by the SCA.
- Boeing was awarded an effort to develop a royalty-free 'core framework' designed to interface with the JTRS SCA.
- Rockwell Collins awarded an effort to examine the inclusion of the Link-16 waveform.
- Harris RF Communications awarded a 2B effort to provide an independent test and validation of the JTRS SCA operating in a manpack configuration. They were to focus

on the trade-offs necessary to obtain an SCA compliant system under strict platform constraints of size, weight, and power in a manpack.
- RACAL also was awarded an effort to provide an independent evaluation of the JTRS SCA. They were to develop an SCA-compliant handheld.
- Vanu's 2B effort awarded an effort to build a handheld radio using COTS devices. This prototype would employ a complete software implementation (no discrete solution hardware) for analog waveforms (AMPS, AM, and FM) and a digital test waveform. Vanu was to evaluate the various trade-offs in performance, when using the JTRS SCA. Vanu was also to collect trend data and conduct a trend analysis related to handheld software radios.

2.8.1.4 Step 2C

The US Army, under JTRS, initiated a procurement of up to 40 prototype JTRS vehicle-mounted radios. These radios are needed to provide secure data networking between mobile users. Such radios would operate in the Tactical Operations Centers (TOCs), for the dissemination of data from Command and Control systems, operating at all echelons from Division to Battalion levels. The network of radios will be scalable to accommodate units needed at a Brigade or Division level. A new data networking waveform to accommodate a network of up to 150 radios is required. An award was made to BAE Systems in June 2000, and they will use their two-channel AN/VRC-99 radio as the basis for the JTRS-2C effort. AN/VRC-99 radio can operate as a time division multiple access (TDMA) radio and as a code division multiple access (CDMA) radio. The Step 2C radio is also targeted to operate in the 225–400 MHz band, and have a frequency hopping spread spectrum capability, with variable data rates from 175 to 500 kbps. Deliveries of the two-channel JTRS-2C radios are planned for November 2001 with deliveries planned primarily to the 1st Cavalry and the third Brigade Combat Team (BCT).

2.8.1.5 Step 3

As of this writing, a single contract is planned for award to a prime system integrator who will develop JTRS ORD software. This prime system integrator will be excluded from the actual hardware development of JTRS radio sets, known as 'Cluster-1' radios. This contractor will be solely responsible for development or procurement of SCA compliant waveforms and will also define the common form-fit-and-function configuration needed to develop both vehicular and aviation versions of the JTRS hardware. This is seen as necessary to ensure the successful porting of the ORD waveforms into JTRS hardware; the Cluster-1 radios produced by two different developers. The prime system integrator will be given the responsibility to choose the two Cluster-1 vendors to work with.

2.8.2 Digital Modular Radio (DMR) [12]

The US Navy, like the other Services, has procured radios based on specific unique operational requirements to meet specific missions. Today, a Navy ship can easily have over 20 different radios. The digital modular radio (DMR), a Navy procurement effort, will provide modular, scaleable, software programmable, reconfigurable digital radios to satisfy near-term ultra high frequency (UHF) and very high frequency (VHF) communications requirements until the JTRS becomes available. The DMR is the US Navy's first radio to be developed to meet the operational requirements as they apply to Navy surface ships, submarines, and shore installations. DMR is a COTS and NDI procurement based on the PMCS open systems architecture.

An award in September 1998 was made to two companies for production of NDI DMR service test modules (STM). One was given to Raytheon and the other to Motorola; these were extendable to incorporate production with unlimited quantities. The STMs were subjected to a 'fly off' for final selection at SPAWAR System Center, Charleston, South Carolina. The final selection of the Motorola Corporation, for the US Navy's AN/USC-61 DMR, was made in February 2000.

Motorola's DMR is an extension of their WITS 6000 series radios, which they developed for commercial sale. The WITS program was Motorola Corporation's continuation of SDR technology resulting from their SPEAKeasy effort. A baseline DMR will be capable of operating on UHF line-of-sight (LOS) and UHF satellite communications (SATCOM), 5 and 25 kHz demand assigned multiple access (DAMA) and non-DAMA channels. It will also provide shipboard single channel ground to air radio systems (SINCGARS). A key element in the Motorola DMR will be its embeddable AIM, which recently received Type 1 Certification from the NSA.

2.8.3 ATLANTIC PAW

Advanced transmission language and allocation of new technology for international communications and the proliferation of allied waveforms, ATLANTIC PAW (A-PAW), is a cooperative international (UK, FR, GE, and US) project to provide interoperability between newly fielded international radios and allow backward compatibility to existing radio systems. A-PAW is an outgrowth and sequel to the previously discussed FM3TR effort. SDRs themselves will not provide all the anticipated benefits without the suite of tools required to expedite changes and new capabilities. The other side of the coin for SDR is the actual software application and the environment under which it is created and managed. A-PAW will develop a common description language, to be employed by all four countries. It will capture waveform specifications, at a high level, and allow the output to be interpreted and coded for each nation's own, dissimilar, programmable radio. This will enable new waveforms to be developed and in an efficient manner, see Figure 2.28.

There are many tools available that attack small areas of the overall problem set but they are not integrable. What is required is the development of an executable specification. The specification itself must be comprehensive enough to capture all the air interface and protocol interoperability requirements. The UK is developing a common description specification language, or a waveform description language (WDL) [13]. Each nation then is expected to develop its own interpreter to transform the WDL output into the implementation-specific details needed to be hosted on national SDR assets. The output will have automatic code generation, which enables direct downloading to the target platforms.

As of this writing, the project consists of a number of tasks, which are shared by the US, UK, FR, and GE. One is the WDL itself, which is the responsibility of the UK. The US leads the task to define the waveform parameter database and structure. Then employing the WDL, the FM3TR enhanced waveform (French led) and the SATURN legacy waveform (German led) will be defined. FM3TR and SATURN waveforms are planned to be imple-

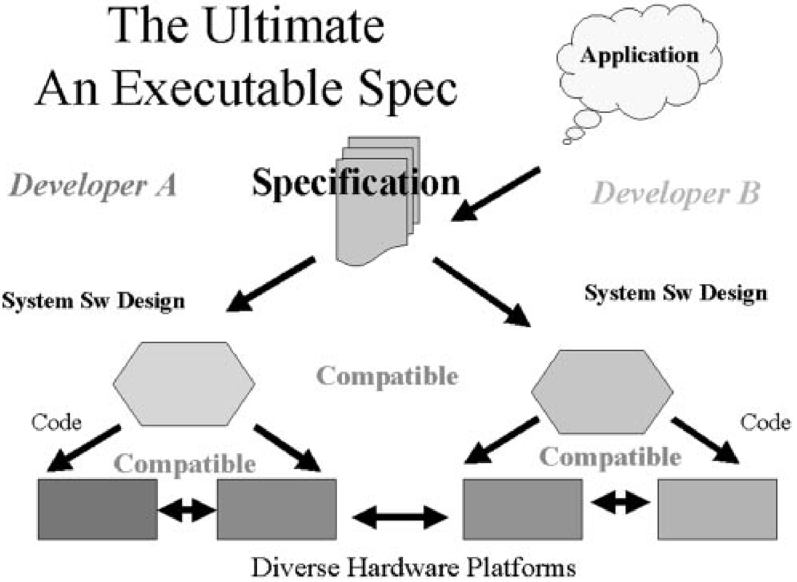


Figure 2.28 Waveform development executable specification

mented onto each nation's respective platform. The culmination of A-PAW will be an international compatibility demonstration using both national SDRs and legacy SATURN radios.

2.8.4 Software Radio Development System (SoRDS) [14]

The SoRDS-2000 (refer to Figure 2.29) evolved from the initial equipment developed in 1999 to support the international FM3TR testing in Germany.

It was developed to serve as a testbed for the development, evaluation, and verification of software communications waveforms and algorithms. SoRDS is expected to provide enhanced capabilities, including 'smart radio' functions to JTRS-like equipment to meet the growing requirements of US military communications. Smart radio functions include bandwidth-efficient covert and jam resistant waveforms, adaptive data rate control, artificially intelligent wireless link and network management, information assurance, and quality of service techniques. SoRDS-2000 needs to have the processing power to develop and evaluate very complex and computationally difficult algorithms. Therefore, a high performance, parallel processing, real-time capability is mandatory. SoRDS-2000 implements a modular and scalable 'Beowulf' architecture (refer to Figure 2.30).

There are four independent single board computers each containing a processor, memory, interface bus, and network interconnect to a host computer via a network switch. Each of these can communicate with each other and other devices on the network. SoRDS-2000 uses a homogeneous cluster of four Compaq (DEC) Alpha 667 MHz processors that have dual independent 100BaseT network interfaces and a PCI mezzanine card (PMC) interface. The host operates under a Linux OS, which supports a parallel processing, message passing

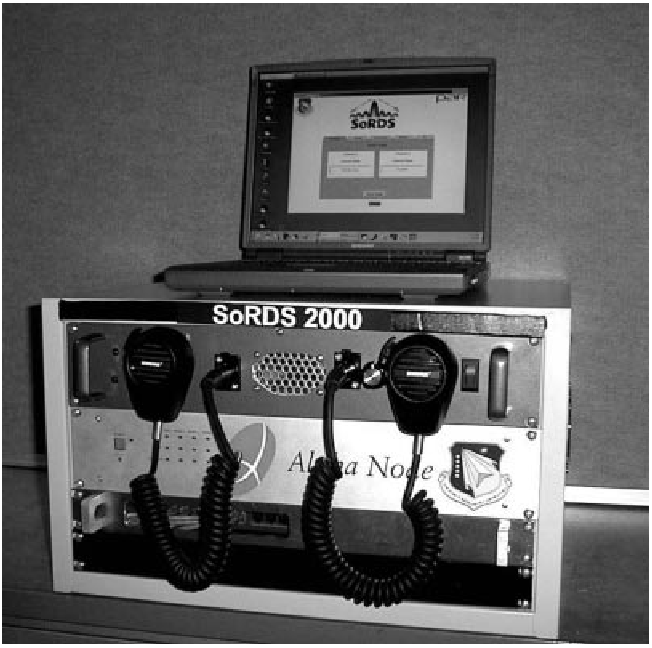


Figure 2.29 Software radio development system (SoRDS)

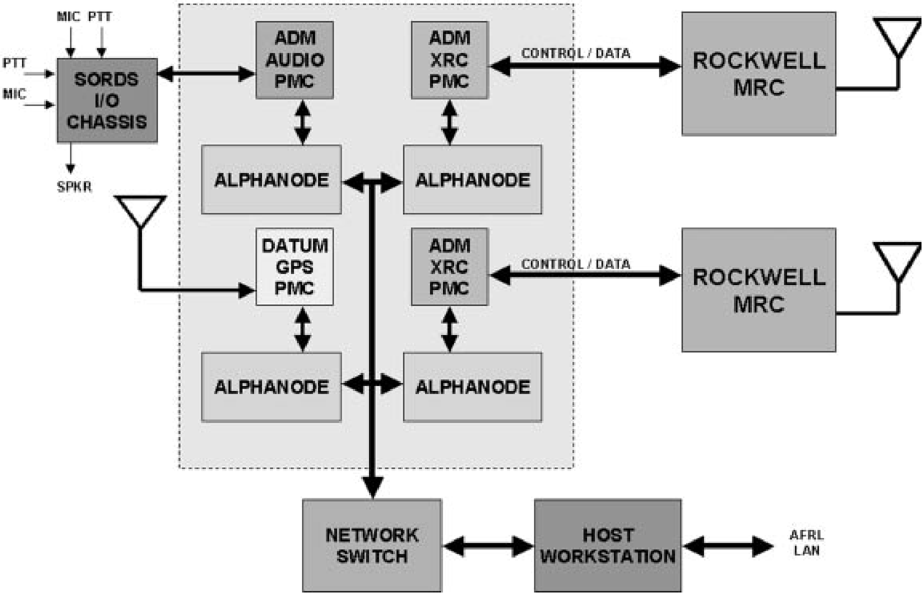


Figure 2.30 SoRDS block diagram

interface (MPI), environment. The SoRDS equipment uses a GPS PMC for timing, and audio PMC for voice and video. There are also two adaptive computing (Xilinx Virtex FPGAs) PMCs for higher speed processes and RF control. SoRDS-2000 is a two-channel system and utilizes a miniature radio codec (MRC), developed and manufactured by Rockwell Collins under the GloMo program, for each channel. A control and data interface module was developed for the MRCs and programmed in VHDL, as was the modem firmware for the FPGAs. SoRDS-2000 is supporting many initiatives at AFRL's Information Directorate, in Rome, New York.

2.9 Conclusions

This chapter has provided a comprehensive history of the evolution of software radio and the way in which over many years defense requirements have been a major driver and funder of software radio. From what today might be seen as quite primitive initiatives fully flexible systems have now been demonstrated, deployed, and are being procured. The US government decision to request the establishment of the MMITS Forum was, with hindsight, a pivotal point in defense initiatives transitioning into the public arena which, together with the subsequent market pull stimulated by the advent of 3G wireless, has seen software radio grow in acceptance and importance in the commercial marketplace.

Defense initiatives in software radio however, as have been outlined, continue and, unhindered by some of constraints of consumer market requirements, are continuing to push back the technological boundaries to establish new possibilities and methodologies which may also in due course find their way into consumer markets.

Acknowledgements

The help and support of several key individuals in providing detailed background material in the preparation of this chapter are gratefully acknowledged. Notably: information for Section 2.1.3 on ICNIA was drawn from a memorandum authored by M. Minges and J. Arnold of AFRL; information for Section 2.3.5 was drawn from the MBMMR final report (dated July 2, 1993) provided to Mr George Singley by J. Oneffur and Major R. Nelson of CECOM/RDEC; Section 2.7.4 was written by Mr Donald W. Upmal WRN Project Leader, US Army Communications & Electronics Command, Fort Monmouth, New Jersey.

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3

The Software Defined Radio Forum

Allan Margulies

SDR Forum Operations Committee

From its early beginnings as the MMITS Forum, the Software Defined Radio Forum, or SDR Forum, has emerged as a driving force in shaping the emergence, commercialization, and standardization of SDR technology on a global basis. This chapter provides a chronology of its origins and development, highlighting its key achievements and contributions.[1]

Several easily noted phases and distinct milestones mark the history of the SDR Forum – starting with the statement of the initial concept through the development of cooperative agreements among a group of organizations with similar interests and then to its evolution into the major international association for those interested in the technology that is likely to become the foundation for advanced telecommunications networks in the future.

3.1 Motivation and Goals

Many successful new ventures are often the result of a confluence of common interests. In a commercial venture, it is sometimes the concurrent emergence of a predicated solution that serendipitously finds a perceived market need. In the case of the SDR Forum, it was the nexus of similar and complementary military and commercial interests to create a mechanism to stimulate the development and deployment of software radios and the underlying technology that makes those radios possible.

3.1.1 The Military Motivation

The genesis of the SDR Forum was in the SPEAKeasy program sponsored by the US Department of Defense (DoD) and managed by the Air Force Research Laboratory, but

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[1] See www.sdrforum.org for details about presentations from past meetings or for more information on current activities.

with all of the military services participating – see Chapter 2 by Wayne Bonser for details of this program.

After the successful culmination of activities in the first phase of this groundbreaking SDR program, in which the team led by Hazeltine (now part of BAE Systems) demonstrated reprogrammability and other significant radio functions, a follow-on activity was planned to begin in the early summer of 1995 to further refine the architecture and implementation. By then, many in the DoD were convinced of the benefits that could be derived from using SDRs, specifically with regard to reducing the acquisition cost of new radios and with mitigating problems associated with lack of interoperability among services and among coalition forces. Therefore, one of the goals for that second phase, in order to maximize the utility of the results to the DoD, was to make the outcome of the program widely available, even to those organizations not participating in the program. In fact, fostering non-military participation was seen as an opportunity to stimulate and encourage the development of commercial products that could be used by the military, thereby reducing the need for special research and development and bringing the military into conformance with commercial products.

To get that kind of information distribution meant that there had to be some vehicle for disseminating the results. In September 1994, during the preliminary planning for SPEAKeasy Phase II, several alternatives were proposed, including the creation of a Multiband, Multimode, Radio (MBMMR) Forum to use the SPEAKeasy results as a point of departure for setting guidelines for radios with an open system architecture. The objective was an agreed-upon architecture and internal hardware and software interface specifications for an industry standard multiband, multimode, programmable radio. With that kind of industry participation, components and production models of such a radio should then be available from third-party vendors.

One common method for developing technology for the US military services is for the service laboratories to issue a series of contracts to one or more industrial organizations. Three separate teams of highly qualified industrial contractors had been identified for SPEAKeasy Phase II, and an open industry-wide consortium would serve both as a neutral ground for discussions between these teams and as a means for getting comments and suggestions from the rest of the communications community. In effect, the rest of industry not involved in the contractual efforts would get an opportunity to see the results of the contracted work and the service labs would get their opinions on the results while there was still time to shape the work.

Thus the concept of an industry association to focus on software radios took root. Around that time, the mid-1990s, several industry associations had sprung up as alliances of companies that were interested in standardizing particular technologies for the purpose of guaranteeing compatibility or interoperability among products. For example, the Asynchronous Transfer Mode (ATM) Forum is a collective effort of more than 600 companies and government organizations interested in asynchronous transfer mode products and services. The members meet at frequent intervals and collectively agree to support specific standards, thereby assuring that products from diverse manufacturers will work together.

The ATM Forum, as well as other industry fora, had established working groups or committees to focus on specific functions. Moreover, the membership of such fora comes from commercial and industrial groups as well as from military and public safety government groups. It was such a paradigm that was seen as the goal for the MBMMR Forum.

The proposed organization was not expected to define all characteristics of SDRs. Physical characteristics (form/fit envelope, weight, battery type, power, etc.), implementation decisions (software language, microprocessors versus field programmable gate arrays, antenna design, etc.), and other internal characteristics would be left up to the manufacturers. In addition, the individual manufacturers, for reasons of competitive distinction, were expected to add features that would enhance radio performance as long as they did not conflict with the basic radio standard.

The goal was to have interoperable radios, and hardware and software modules, available from multiple sources, conceivably even from third parties, thereby reducing non-recurring engineering costs and procurement costs due to competitive economic pressures. Several versions of a SDR could be based on a common hardware suite, which would translate into logistics savings because spares would be procured on a larger base of systems.

Another factor was the need to comply with the DoD's newly established principle of having new systems comply with open system standards as much as possible. (The IBM PC and its clones could be seen as providing an excellent example of an open system.) The hope was that the Forum would be able to define those characteristics that would be necessary to establish an open system; that means having many suppliers, many customers or users, an architecture with a long life, and the ability to easily incorporate technology upgrades.

Additional economic benefits to manufacturers and to consumers were envisaged from this approach because incremental development of new radio models based on existing models, would reduce the development cycle.

3.1.2 The Commercial Motivation

At the same time that the SPEAKeasy II program office was considering how to promote the development and use of reconfigurable radios in a military environment, BellSouth Wireless (now part of Cingular Wireless) was exploring the state of the art in software radios that could be used in commercial wireless networks.

On December 15, 1995, BellSouth released its Software Defined Radio Industry Request for Information (RFI)[2] to "solicit information from suppliers of technology, hardware, software, network and operational support infrastructure and subscriber terminals within the emerging and broader wireless telecommunications industry to implement the concept of Software Defined Radio". This was a defining document in the history of SDRs because, even though it was not the first explication of SDRs, it was the first attempt to define practical terms of use. BellSouth's specific interest was in determining the ability to create a multiple mode wireless communications capability with 'Total System Flexibility' through flexible subscriber sets, base stations, network architecture and service level features, and management interfaces.

BellSouth was concerned about its future investment strategy and the ability to deploy technology that would not become obsolete within a few years. Its statement of requirements echoed that of the military almost word for word when it said that the company was interested in multifunction, multimode, and multistandard flexibility.

The significance of the 70-page RFI, which was released to more than 80 component and technology suppliers, was emphasized by BellSouth's stature in the mobile communications

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[2] The far-sighted BellSouth RFI was authored by Stephen Blust, a chapter contributor to the companion volume [1].

industry. At that time, the company and its partners served almost 6 million cellular, mobile, and digital paging subscribers in 15 countries.

The RFI was predicated on two factors: it recognized that there is no single wireless standard for digital services, and it also recognized that the solutions to the problem might not be fully developed at that time. It even speculated about the possible use of incentives to encourage development of software radio technology by sponsoring industry forums, funding proof of concept studies, or placing advanced orders for equipment.

The RFI sought technology solutions for a fragmented market by posing 55 questions based on time scales of availability ranging from 0 to 3 years, 3 to 5 years, 5 to 10 years, to longer than 10 years. The questions, on topics ranging from market complexity to technologies, were grouped into categories relating to the market environment, standards environment, development drivers, service and capability issues, technology and dependencies, cost, and network issues, with the bulk of the questions focused on this last category.

The market environment section addressed the fragmentation of the consumer marketplace and the proliferation of services offered, the proliferation of standards implemented, and the effect of roaming and mobility (movement between home zones due to changing residences) as distinct from roaming. The services section looked at consumer expectations regarding quality and level of service, multicapability functionality (mixed mode operations, including voice, data, short message service, etc.), multimode operation (revisiting the multistandard issue), and multiband operation to permit cordless operation in the home as well as in personal communications systems (PCS) or cellular networks.

The technology section asked the respondents to consider topics related to handheld subscriber terminals as well as base stations; specifically, it was concerned with digital signal processing elements, batteries, antennas, and architectures. The cost – or, more accurately, the prediction for time-variant cost curves – was also a major factor.

By far, however, the most substantive part of the questionnaire concerned the impact of software radios on the wireless network. This is a particularly sensitive area because a subscriber handset capable of roaming across networks with dissimilar air interfaces imposes a requirement on the host system for interswitch communications and interworking facilities to translate between protocol formats. Alternatively, to accommodate multimode roaming, the base station can be equipped to support multiple air interfaces. The BellSouth approach anticipated a combination of both approaches and asked questions accordingly. In the case of the multimode handset, it envisioned a need for a software download in order to acquire configuration data for the host network, and in the case of an adaptive base station, it postulated a channel reconfiguration based on instructions from the mobile station controller.

The RFI was an attempt to move from the point solutions for wireless services, which had worked well in the past, to a more universal solution that could accommodate a shift to the emerging niche services and protocols while still recognizing the need to accommodate legacy systems. BellSouth had a vision of allowing the network operators to control infrastructure investment while at the same time increasing revenues by offering new services. It clearly recognized the need for continuing technical development and efforts to obtain industry acceptance and commonality.

3.1.3 Common Goals

Although the military and commercial market segment representatives approached the problem from different perspectives, they had common goals. Life cycle costs (non-recurring engineering, logistics, maintenance, and system management), technology independence, flexibility and adaptability, open interfaces, interoperability (in the form of the ability to operate with multiple air interfaces), and ease of operation for the user are all basic requirements for both markets.

Moreover, BellSouth and the SPEAKeasy program recognized the need for a coordinating industry association to become both a champion of the software radio concept and a medium for discussion of details and implementation. Until this time, both of these activities had been proceeding independently, each without knowledge of the other. It was against this background that the SDR Forum began to take shape.

3.2 The Formative Phase – 1995

In much the same way that significant preparatory effort must take place before a new company attempts an initial public offering of stock, significant preparatory activity must occur before announcing the formation of an industry association.

The initial planning efforts for the organization that was to become the SDR Forum were led by the SPEAKeasy program office at the Air Force Rome Laboratory (now the Rome Research Site of the Air Force Research Laboratory), assisted by the MITRE Corporation, a non-profit federal contract research center. The concept was proposed in August 1994, and planning proceeded over the following year, culminating in a meeting held at the MITRE office in Washington, DC, on September 14, 1995. At that meeting, Wayne Bonser, of the SPEAKeasy office, led a group that included representatives of the military service labs involved in the SPEAKeasy program, the Pentagon's Open System Joint Task Force (OSJTF), the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC), and the Telecommunications Industry Association (TIA). This meeting focused on setting goals for the organization and discussions about a preliminary charter for a non-profit corporation loosely based on the ATM Forum model. The nascent organization was tentatively named the Multiband Multimode Radio Forum.

At a follow-up meeting 10 weeks later, also in Washington, a group of MITRE staff supporting the Air Force and the Army, and representatives from Motorola and the OSJTF refined the charter and the name was changed to the Modular Multifunction Information Transfer System (MMITS) Forum to broaden its scope. Wayne Bonser again led the group discussion of the possibility of becoming a working group under the umbrella of another standards development organization (SDO); the primary candidate was VITA/VSO (VME Industry Trade Association/VITA Standards Organization), the American National Standards Institute (ANSI)-accredited VME-bus SDO. It was at this November 30, 1995 meeting that the preliminary vision and mission statements were reviewed, a canonic architecture was presented for consideration, and a timeline for creating the Forum was established.

The draft mission statement established a goal of becoming an international organization to promote the development and acceptance of a modular, reprogrammable system based on an open architecture and accepted standards. The focus was explicitly not a radio, but was referred to as an information transfer device in order to broaden the application to such elements as modems. The group was expected to focus on both hardware and software architecture, and, from the beginning, it was precluded from specifying design or implementation details.

The accompanying vision statement emphasized the open system touchstone and it went on to encourage a competitive industrial base in the market for communications products, technology, and services.

A final planning meeting was held in January 1996 to refine the plans, and then an item was published in the *Commerce Business Daily* announcing a meeting on March 13 at the TASC offices in Rosslyn, Virginia, where it was expected that an industry forum would be formed to address issues related to SDRs.

3.3 The Inaugural Year – 1996

The March 13, 1996 meeting was a full-day event with more than 100 attendees representing federal government groups, defense contractors, and commercial organizations. Discussion focused on issues related to forming an industry association devoted to encouraging the development of a software radio industry. Again, Bonser led the discussion, starting off with a presentation of the need for an industry association. He explained that the strategy until that time had been for each of the military services to develop communications equipment to suit their unique service missions, but that the emerging DoD strategy was to leverage the commercial base and change from the role of a developer to that of an integrator of commercial components. In his opening remarks, Bonser said that this group was "pioneering the way for communications into the twenty-first century". He continued, "I can't guarantee that history is going to be made here today, but we do have the opportunity to profoundly influence the way communications systems – actually, information systems – are developed."

The keynote speaker for the initial meeting was Lennie Burke, of the DoD's OSJTF, who reiterated the description of an open system being one that has many suppliers, many customers or users, a long-life architecture, and the ability to easily incorporate technology upgrades. The IBM PC with its many clones, he said, provides an excellent example of an open system. He went on to describe the DoD's business strategy as one of meeting operational needs at the lowest life-cycle cost and focusing upon the use of commercial hardware and software.

Bonser raised the issue of finding a host organization in order to provide a point of departure for the ensuing discussion of VITA/VSO as a candidate standards organization umbrella for a SDR working group. Bob McKee, who at that time was chairman of the VITA/VSO Board-Level Live Insertion Forum, then used the efforts of his group to illustrate the VITA/VSO standards development process. That process starts with a consensus determination on the need for a standard after which a task group of at least three VSO members is created to develop the standard, and the product is adopted as an ANSI standard after a sequential balloting process. Questions were raised about the ability of VITA/VSO to consider standardizing interfaces that lie outside of the VME framework, as well as about the financial implications of requiring MMITS task group members to be members of VITA. There was considerable interest in creating an independent group, but there was also interest in continuing to explore the option of becoming a task force under another organization. The group determined that more information was needed about both options before a decision could be reached.

The draft foundation documents (the mission statement, vision statement, and draft charter) that had been created by the initial working group in the preliminary meetings were distributed to this group. These documents stimulated questions and discussion about the proposed role of the Forum, and, as with the affiliation question, the group decided to continue development of these documents before making a decision.

Bonser then went on to ask for elections for two interim officers, a Chair and Vice-Chair, to guide the group for the next two meetings (approximately 6 months), at which time permanent officers would be elected. By ballot, Joe Mitola from MITRE, who had recently published his seminal paper on software radio architecture in the *IEEE Communications Magazine*, was elected Chair and Jim Hoffmeyer, from the Department of Commerce's National Telecommunications and Information Administration (NTIA), was elected Vice-Chair.

MMITS Vision

The MMITS vision is to provide high quality, ubiquitous, competitively priced wireless networking systems, equipment, and services with advanced capabilities. This vision includes a view of seamlessness across diverse networks and integration of capabilities in an environment of multiple standards and solutions.

Ease of use, mobility, enhanced productivity and support for lifestyle choices are all wanted by the communication systems users. Convergence among wireless and wired services such as educational, entertainment, and information services requires improved interworking and interoperability.

Consequently, consumers of communication services, communications service providers, equipment suppliers, and maintainers can benefit from open architecture coupled with the software definable networking radio systems developments espoused within MMITS. This community of interest not only includes the needs of the general public, but also includes governments and their requirements for defense, law enforcement, and emergency services, including National Security and Emergency Preparedness.

MMITS Definition

The Modular Multifunction Information Transfer System (MMITS) presents an open architecture for wireless networking systems. Major considerations in networking systems include SDR waveform hardware and software, security, source coding, and networking protocols.

Software defined radios use adaptable software and flexible hardware platforms to address the problems that arise from the constant evolution and technical innovation in the wireless industry, particularly as waveforms, modulation techniques, protocols, services, and standards change.

A SDR in the MMITS context goes beyond the bounds of traditional radio and extends from the radio terminal of the subscriber or user, through and beyond the network infrastructures and supporting subsystems and systems. MMITS is a concept that spans numerous radio network technologies and services, such as cellular, PCS, mobile data, emergency services, messaging, paging, and military and government communications.

MMITS Forum Mission

The mission of the Open Architecture Modular Multifunction Information Transfer System (MMITS) Forum is to accelerate development, deployment, and use of software definable radio systems consistent with the objectives of the above wireless vision.

The MMITS Forum will work toward the adoption of an open architecture for advanced wireless systems that includes the requisite functionality in terminals, networks, and systems to provide ‘multiple capability and multiple mission’ flexibility for voice, data, messaging, image, multimedia, and future needs.

The MMITS Forum shall establish requirements related to the definition of internal and external systems interfaces, modules, software, and functionality that the industry can use as guidelines in building modules, products, and systems.

Further, the MMITS Forum will promote the development of standards for MMITS, including those focused on MMITS equipment and those supporting service application areas, in areas of interoperability and performance and in underpinning core technologies, either directly or through appropriate liaisons to industry associations and standards bodies. The MMITS Forum will pursue industry wide acceptance of these standards.

To assist the wireless and supporting industries in understanding the value and benefit of software definable radio, and in particular, the MMITS vision, the MMITS Forum will also address market requirements, quantify the market, and develop timelines relative to the use of multimode, multiband, and multi-application wireless communications systems.

The MMITS Forum membership shall include telecommunications users, equipment suppliers, and developers of technology, products, systems, hardware, and software, as well as service providers and system operators or any other individual, organization, or entity who has an interest in furthering the objective of MMITS.

Mitola’s goals for the forum fell into three areas:

- first, to leverage the commercial industrial base to develop the components to produce software radios, to obtain the benefits of open competition and open standards;
- second, to remain abreast of global technical developments; and
- third, to seek implementation of standards that are timely and testable.

Mitola foresaw the need to develop a MMITS architecture and core standards.

A motion was presented to appoint a committee to review the foundation documents and to define the scope of interest (topics such as channel coding, RF subsystem, source coding, and information security were postulated). The motion passed without objection on a voice vote, and Mitola appointed the following people, led by Mark Cummings, to what was to become the Forum’s Steering Committee: Bruce Fette (Motorola), Stan Griswold (ITT), Dennis Weed (FAA), Wayne Bonser (USAF), and Robert Moton (BellSouth); Jim Hoffmeyer was appointed ex officio and Allan Margulies served as secretary. The next meeting was tentatively scheduled for June, and the SPEAKeasy home page was designated as an initial web site.

The second meeting of the MMITS Forum, on June 11–12, 1996, was hosted by Motorola at their facility in Schaumburg, Illinois, and, again, more than 100 people attended. This meeting focused on four main topics:

- organizational scope
- military and commercial requirements
- markets issues
- technical committee goals

At this time, with no formal organization yet in place, there was no membership requirement and no treasury to pay for expenses – the meeting expenses had to be covered by the meeting fees or the organizing individuals would have been financially liable. Having Motorola sponsor the meeting was therefore a major benefit, and having the group's web site hosted by the Air Force's SPEAKeasy program also helped during this organizational period.

By the time of this second meeting, the Steering Committee had formed a de facto set of committee assignments: Mark Cummings and Jim Hoffmeyer were acting as Chair and Vice-Chair, respectively, of the Technical Committee; Stephen Blust (BellSouth, who had replaced Robert Moton) and Tom Nicholson (Motorola) were interim Chair and Vice-Chair of the Markets Committee; and Allan Margulies was serving as the Chair of the Operations Committee. In the intervening period, this group had met several times by teleconference to work on the foundation documents, to explore options with respect to organizational issues, and to plan near-term activities. In fact, from the initial organizing meeting in March through the end of the year, the Steering Committee met 17 times by teleconference to plan the Forum's activities. From the beginning, the goal was to foster development and delivery of multiband, multimode radios based on an open architecture, to identify market requirements and to develop standards to meet those requirements.

By the time of this second meeting, all of the committees had defined tasks:

The Technical Committee was to

- assess inputs of user requirements established by the Marketing Committee
- define an architecture that encompasses the superset of requirements
- create subcommittees to define standard interfaces between architectural components
- recommend other standards group liaisons to the Steering Committee
- report draft standards to the general membership for ratification

The Markets Committee was to

- document the markets for MMITS devices
- define the size of each market and its timeframe for implementation
- define each market's user requirements
- provide input to the Technical Committee
- finalize the name of the association

The Operations Committee was to

- publish and distribute documents
- provide minutes of Steering Committee meetings
- send association communications to the membership
- issue press releases

- maintain the association's web site
- maintain membership records
- arrange facilities for general meetings

The focus of the morning session of the first day of the two-day meeting was on markets issues: the multicapability requirements of wireless network operators, projections of future market size, and projections of future service requirements, commercial aviation requirements, the US military's perspective, and UK and NATO military requirements. The afternoon session emphasized technical issues surrounding a possible standard architecture. Presentations focused on planned technology insertion, the experiences of SPEAKeasy Phase I and SPEAKeasy Phase II, and a programmable base station implementation.

One of the administrative issues that was addressed at this meeting was the decision about whether or not to affiliate with a standards-setting organization, an SDO, and if so, which one. VITA/VSO had been proposed at the previous meeting, and the ramifications, benefits, and drawbacks were presented to this group. To a large degree, the rest of the first day was spent establishing common ground with respect to requirements and the state of the art in order to bring all attendees to a shared reference point.

At the end of the day, after the attendees had considered the proposed mission and scope statements (see pp 79–80), they were asked to either ratify those documents or return them to the Steering Committee for further work. With the approval of all attendees eligible to vote, the documents were accepted and the Forum direction had been established. From the beginning, the open system concept was part of the goal for establishing a 'future proof' architecture. The second day of this meeting was devoted to working sessions.

The third Forum meeting was hosted by the MITRE Corporation at its McLean, Virginia, facility in September 1996, with nearly 100 people attending the meeting.

Mitola urged the group to be patient and cooperative and not to merely try to protect proprietary interests. Again, much of the first day was spent reaching for common ground and recapitulating the motivation for creating the Forum. A major effort was also spent in reviewing the goals of developing a larger market sooner and more efficiently, including reduced time to market for equipment manufacturers, faster growth and increased market penetration for carriers, and increased ease of maintenance and lower risk through an evolutionary infrastructure. Taylor Lawrence, of the Defense Advanced Research Projects Agency, provided the keynote address with a talk about the military's perspective of open systems and the digitization of the battlefield. He challenged the Forum to open a dialog between Pentagon executives and their counterparts in industry. Dennis Bodson, of NTIA, provided an overview of the National Communications System and its application to government planning for emergency preparedness.

Throughout the year, the Technical Committee had been meeting regularly by teleconference, and its structure had evolved around subcommittees for applications, form factor, and architecture. The architecture subcommittee had been further divided into working groups on base stations, mobile, and handheld configurations, and the applications subcommittee had created commercial, civil, and military working groups. The Markets Committee announced its intention to release a forecast report that defined the marketplaces and categories of equipment, with the goal of stimulating industry to move forward with the requisite technology to support software radio concepts.

At this September meeting, as had previously been agreed, permanent officers were elected for the Forum. Jim Hoffmeyer and Stephen Blust were nominated for Chair and Vice-Chair; with no other nominations, they were elected by acclamation. At this point, without bylaws or articles of incorporation, the Forum had no other officers.

Because the Forum was still in its inaugural stages, the group discussed other administrative details. In the opening plenary session, Hoffmeyer addressed the issue of the name of the Forum. Some suggestions had been made that the name MMITS Forum did not adequately convey the goals and focus of the Forum to those not already acquainted with it. Hoffmeyer proposed several alternatives such as Multimode Software Wireless Systems, Software and Open Architecture Radio Systems, and others. After a short discussion, he requested a straw poll on whether or not a new name should be sought. Most of the delegates voted to retain the MMITS Forum designation and only six wanted to change the name, so the discussion ended for the time being; it would resurface several times in the coming months.

The issue was then raised as to whether the Forum should affiliate with another group or should incorporate as an independent organization. The Steering Committee had considered VITA/VSO, CTIA, TIA and others as possible umbrella organizations, and they had spoken with two attorneys before deciding to recommend that the Forum incorporate as an independent non-profit organization. This decision was based upon factors relating to independence and scope. As an independent group, the Forum would have more complete control over its own activities. In addition, the Forum's outlook was broader than that of any other group, and the Forum could establish its own processes for document approval. Moreover, incorporation is easy, inexpensive, and quick. The members voted overwhelmingly in favor of an independent corporation.

The Forum's first year, the organizational year, concluded with a general meeting in San Jose, California, in December 1996. The depth of interest of the radio community in software radio technology had been established during the year, and it was significant enough to warrant a permanent organization. So the Steering Committee took advantage of the San Jose venue to meet with and retain San Francisco attorney Chris Martiniak to start working on plans to incorporate. The bylaws drafted by the Steering Committee included provisions for membership requirements, fees, and Forum structure, as well as some interesting administrative provisions. For instance, the Steering Committee explicitly made provision for multiple classes of membership so that small, medium, and large companies, as well as government and non-profit organizations, could be equally represented. They further determined that decisions would be made by majority vote rather than risk the possibility of a deadlock, which could result from a need for consensus; no Steering Committee member could hold two offices (in order to involve as many participants as possible); and voting eligibility would include an attendance factor, not merely the payment of dues, so that members who were not party to discussions could not block progress.

At this general meeting in San Jose, the Forum members got an introduction to European activities in software radio technology from Martin Swinburne, of Orange, who presented a briefing on the European Union-sponsored Flexible Integrated Radio System Technology (FIRST) project. This consortium of vertically integrated companies included network operators, equipment manufacturers, and component manufacturers, as well as academic organizations, interested in developing multistandard, multimode, multiband terminals to facilitate the transition to third generation cellular systems. Swinburne presented a proposed block diagram for such a device and the performance requirements that it would have to meet. He also noted that the consortium was developing a prototype handset using selectable preloaded software modules to adapt to different signal structures and modulation schemes.

The Technical Committee had continued to meet bi-weekly by teleconference, and they indicated their intention to have a draft report out for discussion within a few months, with a final version to be ready by the end of 1997. The report was to focus on radio architecture as modified by the usage domain for which it is intended; that is, handheld units and mobile units would likely have different architectural requirements.

Similarly, the Markets Committee had established a plan to develop a market forecast report to estimate the size of the market for military, civil government, and commercial units. The major issues appeared to be affordability, security, global circulation, and physical factors. Major concerns centered on the possibility of a mismatch between government and commercial requirements. A survey had been distributed prior to the meeting, and the results were discussed at the meeting.

Administrative issues for the Forum still had to be resolved. Bruce Fette was elected Treasurer; Mark Cummings and Dave Murotake were elected Chair and Vice-Chair, respectively, of the Technical Committee; and Lowie Brannon and Bruce Kraemer were elected Co-Chairs of the Markets Committee. Interestingly, early on, Bonser, who had been a moving force in establishing the Forum, had taken himself out of the running for a leadership position because it became evident that a representative of a DoD organization could not and should not have a strong leadership role in the Forum. Specifically, a DoD employee legally could not have such a role because DoD regulations prohibit its employees from having financial responsibilities in outside organizations, and should not have such a role due to the possible perception from commercial organizations and those from other countries that the Forum would be driven by DoD interests.

The Steering Committee announced the dues structure for the nascent organization. Four classes of membership were defined, each with its own dues rate:

- large companies (annual revenue in excess of $100 million)
- medium-sized companies (between $10 million and $100 million annual revenue)
- small companies (annual revenue less than $10 million)
- government/non-profit organizations

It was also at this December 1996 meeting that BellSouth paid its dues and became the charter member of the MMITS Forum.

3.4 The Forum Matures

3.4.1 – Early Results and Liaison with Europe

In February 1997, as the MMITS Forum's Technical Committee was defining a technical architecture for a SDR, the US DoD established the Programmable Modular Communications System (PMCS) Integrated Product Team (IPT) to develop an open architecture for a reprogrammable radio based on commercial technology for DoD acquisition (see Chapter 2 by Bonser). Because some of the IPT members, all representatives of government agencies or their consultants, also participated in the SDR Forum's definition process, the architecture in the Engineering Reference Model, Figure 3.1, that resulted from the PMCS activity was

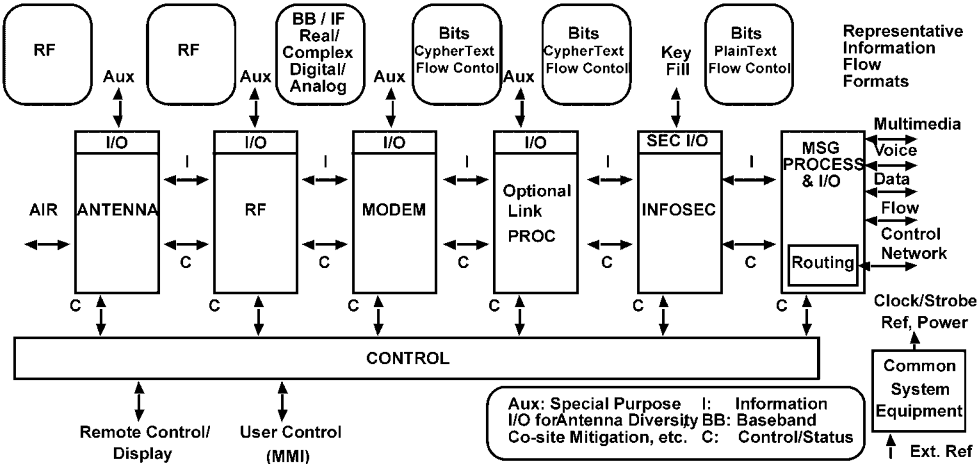

Figure 3.1 The PMCS engineering reference model architecture

submitted as a contribution to the Forum, where it was modified and incorporated into the Forum's Technical Report.

Another product of the PMCS activity that was modified and adopted by the Forum's Technical Committee involved the software applications interfaces that would make the architecture conform to open system standards. This interface definition is illustrated in Figure 3.2.

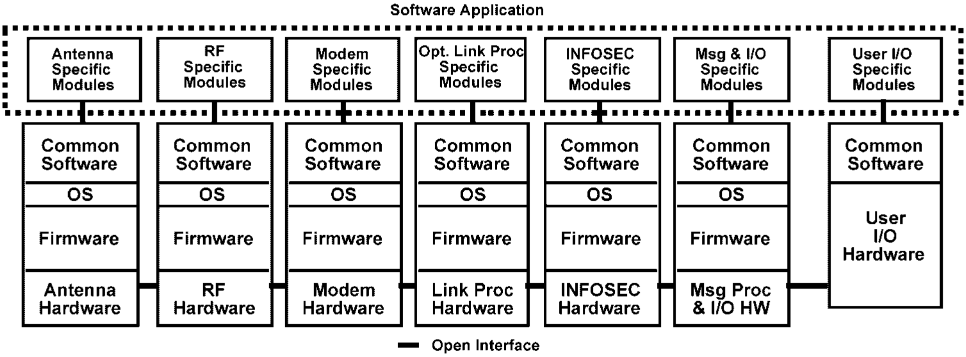

Figure 3.2 The PMCS software applications architecture

These two reference model concepts were the major focus of the first edition of the Forum's Technical Report 1.0, 'Architecture and Elements of Software Defined Radio Systems as Related to Standards', which was issued in July 1997.

Attendees at the March 1997 meeting approved the bylaws as they had been modified by the attorneys, but they also asked the Steering Committee to review the provisions regarding intellectual property in order to allow sharing of technical information while still protecting the intellectual property rights of members. These bylaws then became the basis for incorporating the MMITS Forum as a California Non-profit Mutual Benefit Corporation in March 1997. The intellectual property issues were a topic of intense discussion in the Steering Committee between March and June due to a fear that material disclosed to the Forum would become the property of the Forum. Appropriate wording for an amendment to the bylaws was crafted as a result of discussions between the Forum's legal advisor and the legal teams of several Forum members. The amendment made clear that intellectual property generated by and for the Forum, such as logos or certification marks, was to be protected by the Forum, but that intellectual property generated by an individual member was to remain the property of that member, and rights to that property would not be transferred to the Forum without a contract between the parties. The amendment to implement the intellectual property provisions was approved by the membership at the June 1997 meeting; at that time, a total of 15 paid members of the Forum were eligible to vote.

That year, the Forum began to significantly expand its activities outside of North America. Forum representatives participated by invitation in a European Commission-sponsored Software Radio Workshop in Brussels in May 1997, and then in the European Union's Advanced Communications Technologies and Services (ACTS) mobile communications summit meeting, held immediately prior to the Forum's October 1997 meeting, which was sponsored by Motorola SPS and Orange PCS, in Warwick, England.

By the end of 1997, the Markets Committee had initiated a pair of market demand forecast studies. A contract for the forecast for the commercial wireless market segment was awarded to the Sloan School of Business at the Massachusetts Institute of Technology,[3] and another contract, to study the demand for civil government applications, was given to the State University of New York College of Technology.

3.4.2 1998 – Consolidation and Internationalization

Throughout 1997, the Technical Committee had continued to hold major working meetings, both by teleconference and in person, in addition to those conducted in conjunction with the general membership meetings. Consequently, early in 1998, version 1.1 of the Technical Report was ready for release. By revising the earlier version to include minor architectural changes to better support security concerns, a description of a software download process, and a definition of the software interfaces between modules, this second edition provided significantly more details on the requirements for SDRs.

The software download feature is central to the concept of SDRs. Among other advantages, it will facilitate repairing software errors by downloading patches, it will permit updating applications or installing new applications, and it will allow the addition of air interface options – all without the customer having to return the unit for servicing. Several scenarios were postulated for implementing these software downloads, but three were explored in detail:

- download from a smartcard inserted into a handheld or mobile terminal;
- over-the-air (OTA) download of a module; and
- OTA download of a complete air interface or waveform.

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[3] This methodology and results of the MIT study are summarized in Chapter 4.

Each of these scenarios followed a sequence of initiation, acknowledgment, authentication, capability exchange, installation, and test. Some of these are critical issues. For instance, authentication of the source and destination are important to ensure that the downloaded software is appropriate and legitimate for the receiving device, and capability exchange lets the source know that the destination device is capable of running the downloaded software; that is, all the essential hardware and software components are in place. Some scenarios had additional phases, such as billing and licensing confirmation, which are necessary to meet the economic imperatives. Adequate security is an unstated requisite for all scenarios to prevent spoofing and hacking.

The section on interfaces satisfied one of the primary objectives of the Forum because an adequate definition of the interfaces between modules is one of the stated foundation elements of an open system. For the purposes of the Technical Report, these interfaces were referred to as application programming interfaces (APIs), even though they are not *strictly* software interfaces. This reference makes sense because the term API is well established and has a connotation of providing a level of abstraction appropriate to define interface design information. Also, the designers recognized that functions performed in software in one instantiation may be performed in silicon in a subsequent implementation, and the interface should be unchanged.

The APIs were defined at several different levels of granularity to allow for different implementations to achieve common goals, and they were designed to permit future expansion of capabilities. Again, this designation satisfies one of the basic objectives of the Forum by allowing manufacturers to select their own design and implementation in such a way as to maximize their own value while still meeting the interface constraints. In addition, although the initial definition of the APIs looked like that of a message-passing interface, that situation could change in the future, especially because there were ongoing discussions pertaining to the use of formal design languages. In June 1998, version 1.2 of the Technical Report was released with an enhanced description of the APIs and with further definition of the API messages needed for the software download process.

During the year, the DoD Joint Tactical Radio System (JTRS) Joint Program Office (JPO) had initiated its effort to define a standard architecture for the US military community (see Chapter 2 by Bonser). As with the PMCS activity, many of the participants in the JTRS program were also participants in the SDR Forum, so the results of that program also fed into the mobile architecture being proposed for the Forum.

By the end of the year, version 2.0 of the Technical Report had been produced. This document not only was restructured to make it easier to understand, but also it added more detail on the APIs and software download process, it presented enhanced architectures for the mobile and handset devices, and it showed the results of the initial activity in base station and satellite areas.

While the Technical Committee was working on the standards definition, the Markets Committee was obtaining the data to forecast market demand for SDRs. The MIT study was completed early in the year and was presented at a media event in San Francisco in May. This study, which focused on the commercial wireless industry, was augmented with other data to create the Market Demand Report ‘Software Defined Radio: a Window of Opportunity in Wireless Communications’, which was released in November.

During 1998 the Forum continued its outreach activities to Asia and Europe. Forum representatives participated in a workshop sponsored by the Japanese Institute of Electronics, Information, and Communications Engineers (IEICE) Software Radio Working Group in Tokyo in April 1998 and at the May general meeting of the Forum, Professor R. Kohno, Chair of the IEICE group, presented the results of that workshop and described the technical progress being made in Japan (for an update of this, please see Chapter 8). In June, the Forum participated in the First International Software Radio Workshop, jointly organized with the European Commission and collocated with the annual ACTS summit meeting held in Rhodes, Greece, and held its September meeting, hosted by Rohde and Schwarz, in Munich, Germany.

Continuing discussions regarding confusion over the MMITS acronym led the Steering Committee to seek a more readily identifiable name for the Forum and, in May, the Committee suggested to the membership that the title Software Defined Radio Forum would more readily convey the purpose of the Forum. By the end of the year, the 27 members of the Forum had formally approved the new name, and the legal process of changing the name had been completed.

3.4.3 1999 – Globalization and Growth

In February 1999, the Forum sponsored a day-and-a-half track on SDRs at Penton Publishing's Wireless/Portable industry conference in San Jose, California. The track, dubbed 'SDR'99' by the Forum and led by Shinichiro Haruyama, of the Sony Computer Science Lab in Tokyo, featured a dozen speakers who made presentations and who participated in panel sessions on the changing and expanding requirements of next-generation wireless communications and network devices. They defined the features needed for the new networks, presented an evaluation of the state of the art and a critical assessment of the future for SDR technology, and then described the challenge to be met in the shift away from a hardware-centric design for radios toward a new paradigm in which implementations are a changing mix of hardware and software. SDR'99 also featured an overview of the SDR market based on the Forum's Market Forecast report.

Continuing the cooperative activities with the IEICE Software Radio Study Group, the Forum's general meeting in March 1999 was held at Yokosuka Research Park, one of Japan's major communications research centers. The first 2 days of the meeting followed the Forum's usual working session agenda, but the third day was given over to the study group's technical presentations. Similarly, in September, the Forum held a meeting in Europe; the venue was Stockholm, and the host was Ericsson.

Other Forum activities during the year included raising the level of cooperation with the FCC's Office of Engineering Technology (OET). The Forum had been in contact with that office in 1998 through presentations, informal discussions, and teleconferences to ensure that software radios were recognized as an emerging technology that could be affected by the regulatory process. That fairly low level of interaction was stepped up in 1999 as the Forum discussed the need for international agreement and consistency in the regulatory process to facilitate global circulation of cellular handsets. The firm of Harris, Wiltshire & Grannis was retained as the Forum's regulatory counsel to help the Forum suggest inputs to the FCC's planned Notice of Inquiry (NOI) and Notice of Proposed Rule Making (NPRM) process regarding software radio technology.[4]

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[4] Mike Grable of Harris, Wiltshire & Grannis describes the evolution of the FCC's SDR regulatory activities in the US in Chapter 11.

To facilitate changes to the Forum's Technical Report, the Technical Committee contracted with an editor to participate in Technical Committee meetings and to update the Technical Report. Version 2.1, with added sections on the mobile radio software framework, base station architecture, and smart antenna definitions, was released in November 1999. The mobile radio architecture, modeled on that of the JTRS JPO, was based on an object-oriented conceptual model with a Core Framework, an Operating Environment, and a Rule Set, with the design rules embedded in the attributes.

By the end of 1999, the Forum had 78 members.

3.4.4 2000 – Standards – Facilitation of the Market

The Forum's emphasis on regulatory issues increased in 2000. On March 17, the FCC issued its NOI[5] on SDRs (ET Docket Number 00-47), asking for comments from the public "to help us evaluate the current state of software defined radio technology and to determine whether changes to the Commission's rules are necessary to facilitate the deployment of this technology". This step is often a precursor to a proposed change in the Commission's rules.

The NOI asked 28 specific questions in the following general categories relating to the SDR technology:

- The State of Software Defined Radio Technology
- Interoperability
- Improving Spectrum Efficiency and Spectrum Sharing
- Equipment Certification Issues (including Security Issues)

In a statement accompanying the NOI, Commissioner Susan Ness expressed her view of the technology and gave some insight into the FCC's perspective when she said, "I am bullish about the prospect of 'software defined radio' … that will allow communications equipment to adapt to multiple standards and add service features without changes to the equipment's hardware." She continued, "it has the potential to add new meaning to the words 'anywhere, anytime'".

In April, the Forum sponsored an all-day regulatory workshop in Washington, DC, in order to prepare the Forum's response to the NOI. In its submission to the FCC, the Forum noted the importance of the need to establish rules for SDRs in order to encourage the research and development of the technology. The Forum reasoned that manufacturers may not be willing to make investments without knowing what rules and regulations would be applied to their products. Moreover, the Forum made the point that regulatory efforts must address global issues, not just national ones, if they are to accommodate global circulation of user terminals. The Forum then went on to discuss each of the Commission's questions in detail. In general, the Forum adopted a position that no new regulations were necessary for SDRs because, to a large degree, the technology merely replaced existing functions currently performed in hardware with a software implementation. The exception to this was the need for minor changes in the rules on equipment modification and relabeling so that all information currently required to be displayed on an FCC label could instead be made available on a user display screen, allowing thereby for functionality and labeling of products in the field to be changed.

Twenty-four organizations responded to the Commission's NOI; most of them agreed

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[5] See Chapter 11 for further detail of the FCC process and activity.

with the Forum's positions, but some did not. For instance, the Federal Law Enforcement Wireless Users Group was concerned that an intelligent SDR could disrupt public safety operations when looking for unused channels. As is customary, the Forum, as well as nine other organizations, took advantage of the opportunity to present reply comments to affirm supporting positions and rebut opposing positions, as well as to clarify or restate their own positions. In its reply comments, filed on July 14, 2000, the Forum pointed out that "it is extremely important for the Commission to avoid prematurely setting standards or rules that freeze SDR in its current state of development and unnecessarily stifle commercial innovation". To encourage the Forum's continued participation in the NOI/NPRM process, Dale Hatfield, head of the FCC OET, presented the keynote talk at the Forum's June meeting in Seattle.[6]

As was expected, the FCC followed the NOI with the release of an NPRM. On December 8, the Commission announced its intent to amend its rules and streamline equipment authorization procedures for SDRs. It proposed a new Class Three permissive change that would allow equipment manufacturers to modify the frequency, power, and modulation of SDRs without the need to file a new authorization application. In addition, the Commission suggested permitting electronic labeling of SDR devices so that third parties could also modify a radio's technical parameters without having to return it to the manufacturer for relabeling. In addition, on December 1, the FCC announced a policy for "Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets", in which they proposed rules to enable licensees with unused spectrum to lease it to others who can put it to use. Because licensees obtain spectrum rights through a 'primary' spectrum market, such as an auction, the lessees would be operating in a 'secondary' market. The intent is to put to use spectrum that would otherwise remain idle, thereby possibly relieving some of the demand for new spectrum.

While the Regulatory Committee was working on the FCC issues, the Markets Committee was involved in creating the Forum's first annual technical products exposition. Ten companies exhibited their SDR-related products at an evening session during the June 2000 meeting in Seattle; the booths included examples of components, systems, and test equipment. In addition, the Markets Committee undertook a redevelopment of the Forum's web site using contractor support to redesign the site.

For the first time, the Forum held five general meetings during the year; three in the US, one in Europe, and one in Asia. The first day of the April 2000 meeting in Seoul, Korea, was a Software Radio Workshop sponsored by the Radio Communications Broadcasting Committee (RCBC) of the Korea Electromagnetic Engineering Society (KEE). This workshop consisted mostly of presentations by representatives from Japan, Korea, and the Republic of China, which highlighted the state of the art of software radio research in Asia.

After several meetings with the Mobile Execution Environment (MExE) Forum of the 3rd Generation Partnership Project (3GPP), the SDR Forum entered into a liaison agreement with that group to coordinate software download activities.[7]

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[6] The Seattle meeting also saw invited presentations from Japan and from Europe (from the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE). These technical activities are described, respectively, in Chapter 8 and in the chapter by Moessner in the companion volume to this book *Software Radio: Enabling Technologies*, edited by W. Tuttlebee, published by John Wiley.

[7] Chapter 9 describes the MExE standard and its positioning as a first step to global SDR standards.

The September meeting in Paris was hosted by Thales and included a review of military and commercial software radio activities in Europe. This meeting also included the initial meeting of the Forum's Roadmap Task Group (RTG), which had been chartered to develop an updated multiyear roadmap of SDR in the commercial wireless, civil government, and defense markets. Also at this meeting, the Technical Committee initiated discussions about restructuring to create two major subgroups, one for commercial wireless interests and the other for government-related and other activities.

At the annual meeting in Mesa, Arizona, in November, the Steering Committee announced three major bylaws changes:

- three additional Steering Committee positions were created to accommodate representation from the three ITU regions;
- the Chair of the Regulatory Committee was elevated to a Steering Committee seat; and
- only one representative per company, or group of related companies, was permitted to sit on the Steering Committee.

At the time of the annual meeting in November, the Forum had 120 members, with 16% of the members from ITU Region 1 (Europe), 25% from ITU Region 3 (Asia-Pacific), and 59% from ITU Region 2 (Americas).

3.4.5 2001 – Moving Towards Commercialization

The Forum's focus on regulatory issues continued into 2001. Lisa Gaisford, Deputy Chief of the Policy and Rules Division of the FCC's OET, keynoted the February meeting in Atlanta, Georgia with a discussion about the growth of the wireless industry and the need for spectrum efficiency. In this context, she quoted FCC Chairman Michael Powell as saying, about software radio technology, "the potential of this technology is immense – it cannot be overstated". Likewise, Hiroshi Asami, Director of Electromagnetic Environment Division, Telecommunications Bureau, Japanese Ministry of Posts and Telecommunications was the keynote speaker at the Tokyo meeting in April. He also referred to the growth in wireless services, and reaffirmed the need for spectrum efficiency as he talked about a paradigm shift in manufacturing from production of hardware to production of software. Also, the Regulatory Committee responded to the NPRM on software radios and to the secondary spectrum policy that had been published in December 2000. In addition, the RTG updated and expanded its roadmap for future Forum activities.

In comments regarding the NPRM submitted in April, the Forum supported the Commission's conclusions and actions, suggesting that the definition of a SDR be appropriately crafted to be neither too restrictive nor too loose because technological advances will make it increasingly difficult to separate 'software' from 'hardware'. The Forum also endorsed the proposal for permissive Class 3 changes, as long as the policy also allows for the possibility of third-party alterations if the original manufacturer opts for an open system design. Most important, the Forum supported the possibility of electronic labeling to avoid the need for expensive and inefficient physical relabeling.

The Forum addressed the secondary markets issue as one that SDR technology will facilitate because the technology will allow wireless systems to adapt flexibly to the frequency, modulation, bandwidth, and power requirements of various service rules. The SDR technology will also facilitate the rapid deployment of new technologies, such as smart antennas, and it will permit the introduction of more spectrum efficient modulation techniques as they become available.

The RTG enhanced and expanded its roadmap to create a capstone strategic plan that all of the Forum's working groups could use for guidance. The Forum has traditionally been contribution driven, with working groups pursuing topics raised by its members. The RTG roadmap provides a time-phased common plan leading to mutually supporting outcomes across market segments in near-term, mid-term, and far-term timeframes. Each working group can then develop its own approach, products, and plan for meeting those goals.

Coordination between the Mobile Working Group (MWG) and the JTRS JPO also increased as the MWG held meetings outside of the Forum's general meetings in order to evaluate the software radio architecture developed under the auspices of the JPO. This was done with the intent of providing feedback to the JPO with suggestions from industry regarding improvements and enhancements.

3.5 Conclusions and Future Outlook

The SDR Forum today has come a long way from its early origins. Clearly it has advanced very substantially in achieving its vision and mission. Despite its now very considerable membership and participation from companies in the commercial wireless industry the Forum continues to retain a base of participation from the defense community, ensuring a continued cross-fertilization of technology and ideas, rarely seen in other such industry fora. The achievements of the SDR Forum in promoting awareness, development and commercialization of the technology are already considerable; however, mass commercialization still lies ahead. The final verdict on its achievements will be written perhaps in 5 years time.

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[1] "Software Based Radio", Stephen Blust, in "Software Defined Radio: Enabling Technologies", ed. W. Tuttlebee, published John Wiley & Sons, Ltd, Chichester, 2002, ISBN 0470 84318 7.

Part II

Market Opportunity and Requirements

4

A Market Perspective: Software Defined Radio as the Dominant Design

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Competing and often incompatible standards, modes, and frequencies now characterize wireless telecommunications services. The existence of so many competing techniques for addressing the same set of challenges is intriguing, and unique to personal communications. Almost all other areas of information technology have quickly converged into one or two standards, with videotape formats and personal computer operating systems being two well-known examples. For the wireless communication market, this heterogeneity not only poses problems for highly mobile users attempting to roam between different types of networks with phones that work over only one air interface; it could also threaten to stunt market growth and delay the introduction of many lucrative new wireless services.

Software defined radio (SDR) is a rapidly evolving technology that provides an efficient and comparatively inexpensive mechanism for the production of multimode, multiband, multifunctional wireless devices that can be enhanced using software upgrades. Software defined radio enables flexible operation across a range of existing voice and data services, along with the ability to adapt to new voice and data services as they are developed and launched, thus addressing many of the most challenging issues confronting the wireless industry. An intriguing question, from both a technical and business standpoint, is whether the compelling benefits of SDR and the current market turbulence in wireless communications may indeed lead to the emergence of SDR-based equipment and services as a dominant design throughout the wireless industry.

This chapter summarizes the results of a detailed study [1], sponsored by the SDR Forum and carried out by a team from the Management of Technology (MOT) Program at the Massachusetts Institute of Technology (MIT) Sloan School of Management, to assess the potential for SDR to emerge as a new dominant design. The study was carried out at MIT between September 1997 and May 1998, and combines extensive interviews of industry leaders with a detailed statistical analysis of factors most strongly influencing the evolution of wireless communications. In addition, this chapter also summarizes key SDR standards, regulatory, and trial system initiatives undertaken by the SDR Forum from 1998 to 2001 based upon the results of the above study.

4.1 Outline of the MIT Market Study

The four-part MIT study was carried out to assess the strategic role of SDR in meeting future wireless communication needs. In particular, the potential for SDR to emerge as the dominant design for future generations of wireless communications systems was examined in detail. Owing to the complex and global nature of the wireless communications industry, the value chain shown in Figure 4.1 was utilized as a framework for the study. Six key links are shown, from end users to component manufacturers. Two additional groups, government and regulatory agencies, together with industry opinion leaders, flank the outer edges of the value chain. While the elements of the value chain remain consistent between regions, the relative power wielded by each group and the relative strength of the relationships between the various groups differ significantly from region to region. Government and regulatory agencies in particular play significantly different roles steering the wireless industry throughout the world. There is a very large and growing number of organizations that offer products and services throughout the wireless industry. However, each of these different organizations may participate in more than one group within the value chain. Regional alliances also play a pivotal role in determining which standards and technologies ultimately emerge.

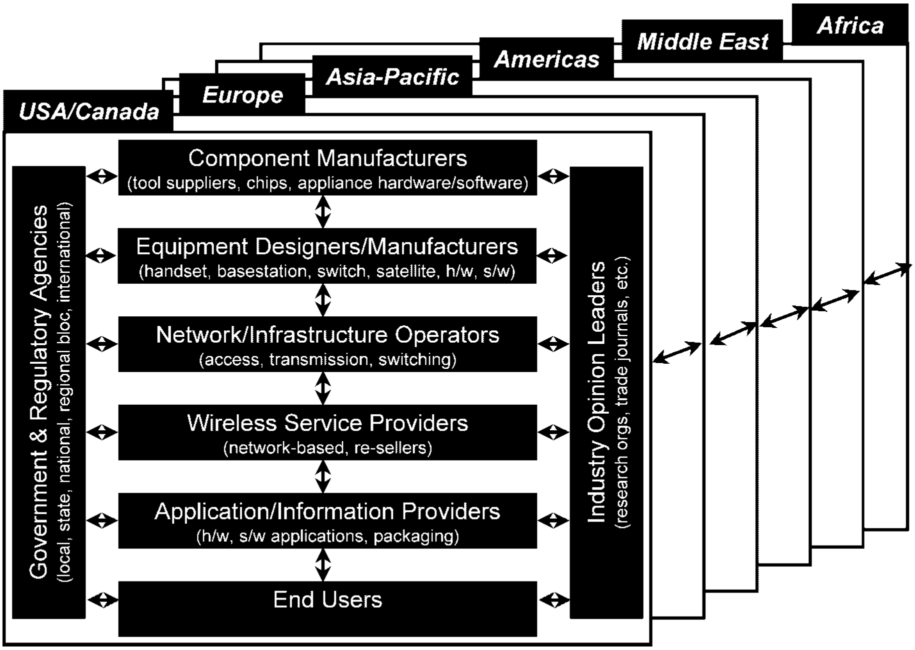

Figure 4.1 Wireless communications industry value chain (note: ‘Americas’ refers collectively to Mexico, Central America, South America, and the Caribbean)

With the above value chain as a first foundation, SDR was evaluated in terms of its potential to emerge as the dominant design for future generations of wireless communications systems. Figure 4.2 presents an overview of the corresponding four-part study undertaken at MIT. Important and relevant lessons derived from recent studies of survival in rapidly changing industries were first reviewed. This part of the study drew its conclusions from the recent business literature on technological innovation, the emergence of dominant designs, and the survival of firms in such industries.

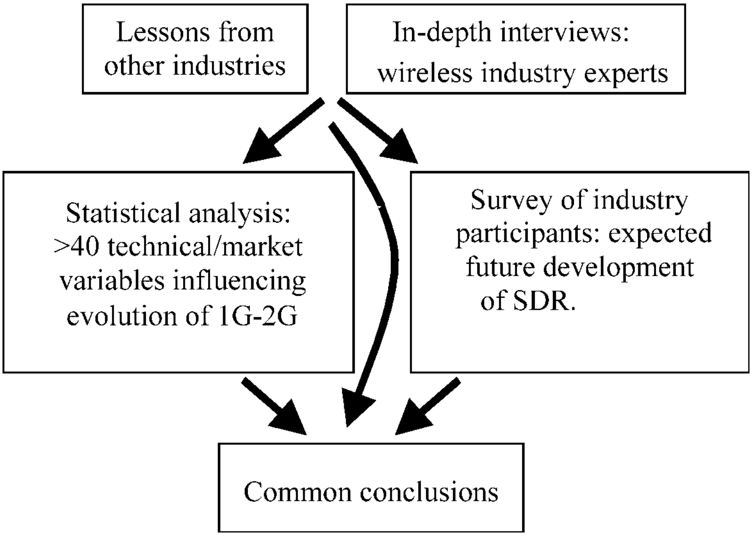

Figure 4.2 Overview of the four-part MIT study of SDR evolution

In-depth interviews were next carried out with industry experts in order to map out the most strategically important features on the wireless standards 'battlefield' from the perspectives of a wide variety of players spanning the wireless industry value chain. The questions asked in these interviews were designed to determine the level of awareness of SDR in the wireless industry and the likely receptivity of the wireless industry to SDR innovations in wireless equipment and services.

Third, the evolution of first- (1G) and second-generation (2G) wireless standards was analyzed in detail, in order to identify and extrapolate potential success strategies for any proposed future wireless standards. Data were collected for over 40 variables (see Appendix A to this chapter) related to numbers of subscribers, subscriber market shares, regional adoption of analog and digital standards, handset and infrastructure equipment manufacturers, government support for the development of standards and technologies, technological performance, and rate of technological innovation. The above data were assembled on a quarterly basis covering the period 1983–1998 (first quarter), for all major regions shown in Figure 4.1. Extensive regression analyses (see Appendix B to this chapter) were carried out for all major 1G (analog) and 2G (digital) wireless standards. By analyzing the growth in the number of subscribers for companies grouped around various wireless standards, it has been possible to identify factors influencing the eventual success or failure of each standard. This approach is similar to recent studies that build upon the tools of evolutionary biology to assess probabilities of failure for firms within an industry. The results have been used to assess the likelihood of SDR emerging as the ‘dominant design’ for third-generation (3G) wireless connectivity.

Finally, wireless industry participants were invited to share their knowledge, expertise, and expectations concerning the possible future evolution of SDR-based products and services. Data were gathered to investigate the degree of market consensus as to the key design elements and rate of market penetration of SDR-based products. Figure 4.3 shows the breakdown of participants in the interview and survey components of the study, in terms of their corresponding membership within the wireless industry value chain (Figure 4.1). Participants were drawn more or less evenly from organizations representing the three most prominent geographical blocks shown in Figure 4.1: US/Canada, Europe, and Asia-Pacific.

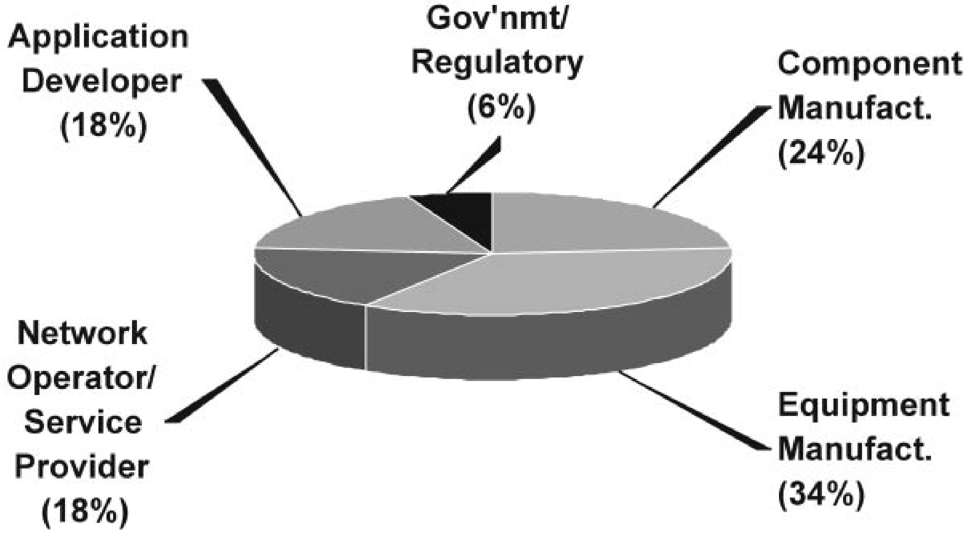

Figure 4.3 Breakdown of value chain representation in the interview and survey components of the study

4.2 Emergence of Dominant Designs

4.2.1 Design Hierarchies

Many competing solutions are being pursued in the wireless communications industry in an attempt to remedy the proliferation of wireless standards, the extreme cases being an all-silicon solution and an all-software solution. Most industry specialists who were interviewed during the course of this study conceded that the collision of the cellular telephony and personal computer industries favors the eventual emergence of software-based SDR solutions as the dominant design for a broad variety of ‘hybrid’ handheld products. However, the severe constraints on size, power consumption, and cost imposed by consumer handheld device markets still pose several technical challenges, and substantial hardware solutions will be required in order to realize the full potential of the SDR-based mobile communications devices.

Which of these two alternatives emerges as the ‘dominant design’ will be determined by the interplay between technical and market choices. The design hierarchies [2] approach shown in Figure 4.4 is a useful means of representing the evolution of a dominant design. Within an industry, each choice of a core technical concept establishes a path of technical progress, or a technical trajectory; there are two such trajectories shown in Figure 4.4. The subsequent series of technical decisions about the product’s design evolution are constrained by both prior technical choices and by the parallel evolution of customer preferences. A dominant design which emerges as the final outcome need not represent a radical change, and is indeed more likely to result from the creative synthesis of available component technologies and the existing knowledge about customer preferences into innovative new product architectures.

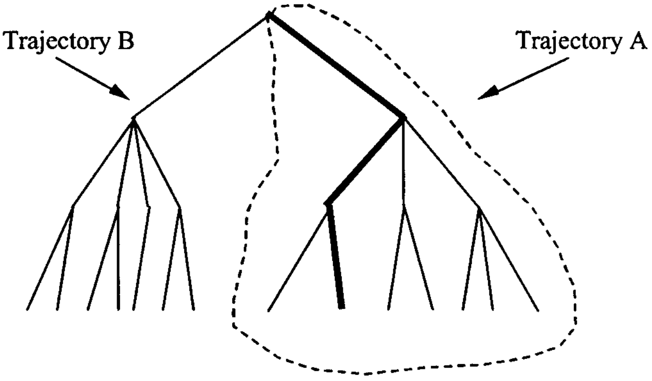

Figure 4.4 Emergence of a dominant design

This latter point is important to appreciate, since SDR itself is not a single technological breakthrough. Rather it is a collection of implementation technologies that enable greater flexibility in a variety of mobile wireless products. The common bond among all SDR technologies is the practical ability to reprogram, or configure, a given radio function after the point of manufacture. The challenge is to exploit such configurability to accommodate the many facets of reconfigurable mobile communications, including network/terminal cooperation for seamless interstandard handoff, quality-of-service (QoS) management, secure software download mechanisms, terminal software architectures supporting reconfiguration, configuration management, capability negotiation, and so on. The dominant design may not be optimized in a broader context, but rather a design that becomes an effective standard. Hence it is expected that standards-related activities will be critical to the eventual emergence of SDR as a dominant design. Given the international nature of mobile communications and the limited availability of wireless spectrum worldwide, efforts to coordinate the SDR-related initiatives of standards and regulatory bodies in America, Europe, and Asia will likely be required.

In light of these latter remarks, it is critical to examine customer and market needs that can justify the pursuit of SDR technologies. The evolution of the wireless industry to date has been very similar to the case depicted in Figure 4.4. Analog and digital paths have been established, and both of these have subsequently split into several different air interface standards operating within several different frequency ranges. Several well-established trajectories have emerged to become today's dominant air interface standards, but the demand for new high-speed wireless services is poised to trigger further evolutionary steps. Software defined radio technologies will likely have a much greater impact on the wireless industry if they can be successfully promoted as dominant design elements that enable the creative synthesis of existing wireless technologies and standards, rather than as a radical leap to a new trajectory.

4.2.2 Lessons from Other Industries

The study of technological innovation has assumed great importance for today's rapidly advancing technology-based industries. Software defined radio innovations have the potential to disrupt the market for existing wireless communications platforms (i.e. the traditional approach), and to become either a new dominant design or to deliver important elements of a dominant design.

A dominant design in a product class is, by definition, the design that wins the allegiance of the marketplace. Competitors must adhere to such a design if they want to command a significant market share. The dominant design may take the form of a new product or a well-defined set of product features. Often, the dominant design is not a major innovation, but rather a design that synthesizes individual innovations introduced independently in prior product variants. For example, the IBM PC format quickly became the dominant design in its market, even though it contained little in the way of breakthrough technology. It did, on the other hand, integrate into one product many familiar elements that had individually proven their value to computer users. A dominant design typically satisfies the requirements of many customer segments, although not to the same extent as designs customized for each individual segment. The dominant design typically does not achieve the most extreme technical performance available in its product class. Its performance is a compromise between technical possibilities and market choices.

The emergence of a dominant design is also determined by the interplay between technical and market choices as a function of time. Many factors other than technology and design superiority come into play [3], including:

- collateral assets [4], such as market channels, brand image, or customer switching costs;
- network externalities in the market, such as additional infrastructure that must be installed before an innovation can be widely adopted;
- strategic maneuvering at the firm level, a well-known example being JVC (VHS) versus Sony (Betamax) in the battle for videocassette recorder standards dominance;
- communication between producers and users;
- government regulation and/or purchasing power.

The above five factors will all be important to the future development of SDR-based equipment and services.

The emergence of dominant product designs has been investigated to date predominantly as a factor affecting the survival of firms within an industry. In particular, the emergence of a dominant product design has been revealed as a watershed event that drastically reduces the probabilities of success for subsequent entrants [5–9]. A clear distinction has been made between competence-destroying innovations (typically introduced by new firms, and leading to increased market turbulence) and competence-enhancing innovations (typically introduced by existing firms and leading to decreased market turbulence [10]). The tools of population ecology have also been employed to identify those forces that most powerfully affect the probabilities of survival for firms confronted with technological innovation [11,12]. These latter tools have been exploited to analyze the survival statistics of high-technology firms within turbulent industries [6].

Figures 4.5 and 4.6 illustrate the impact of dominant design emergence within rapidly changing industries. In Figure 4.5, the period preceding the emergence of a dominant design is shown to be characterized by an increasing number of market entrants [9], while the period immediately following the emergence of a dominant design is typically marked by many unsuccessful competitors being forced to exit the industry. One important finding is that there is very often a 'window of opportunity' in the industry just prior to the emergence of the dominant design, during which entry is particularly advantageous.

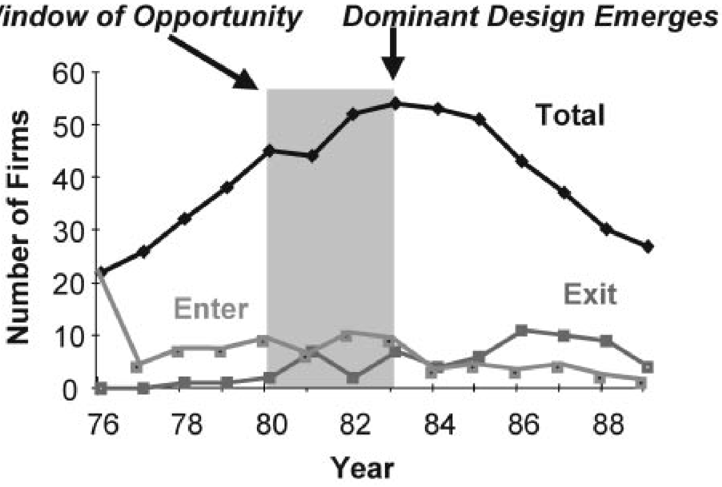

Figure 4.5 Typical influence of dominant design emergence on the number of firms in an industry

The second insight relates to the risk of betting on new technologies, versus betting on new markets. It has been found that firms whose entry strategies involved using proven component technologies in innovative product architectures that facilitated the emergence of new market segments, had significantly higher probabilities of survival than did firms that entered established market segments with new component technologies that offered better performance. In other words, entry strategies that entail *market* risk (entering an emerging market with proven component technology) may be less risky than strategies that entail *technological* risk (entering an established market with new, higher performance component technology) [13]. This

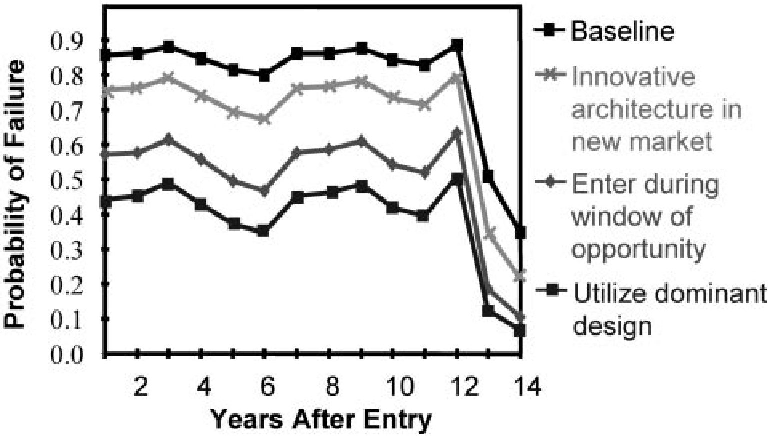

Figure 4.6 Typical impact of dominant design on a firm's probability of failure

risk does not appear to be appreciated by many potential entrants into the market for advanced wireless communications products and services, where SDR is being pushed as a collection of higher performance component technologies without thoroughly assessing the overall product architecture opportunities and emerging market needs which these technologies might address.

Figure 4.6 shows how, in addition to pursuing what would emerge as the dominant design, choosing an appropriate combination of innovation and entry market significantly reduced disk drive firms' probability of failure [9]. Architectural innovators entering new markets presented a much lower hazard than did baseline firms. For the example shown in Figure 4.6, the probability of failure for a baseline firm during its sixth year of business was much higher than it was for a firm that was an architectural innovator and entered into a new market.

The main hypotheses supported by previous studies of dominant designs can thus be summarized as follows:

firms that adopt the dominant design features will be less likely to exit from the industry;

- firms that enter the industry during the 'window of opportunity' just prior to the emergence of the dominant design, will be less likely to exit; and
- firms that introduce architectural innovations into new markets will be less likely to exit than will firms that introduce component innovations into existing markets.

All three of these hypotheses are likely to apply to the wireless industry as follows:

- firms that adopt the dominant design (in this case, SDR) will be less likely to exit from the industry or lose market share;
- firms that enter the industry during the window of opportunity just prior to the emergence of the dominant design will be less likely to exit. The dominant design (SDR) is expected to emerge in the 2000–2001 timeframe, with continued maturation and acceptance occurring over the period 2000–2005 and beyond;
- firms that introduce multimode, multiband, multicapability innovations into new wireless

communications markets will be less likely to exit or lose market share than will firms that introduce traditional component innovations into existing markets.

4.2.3 S-curves – Disruptive Technologies

The performance offered by a new technology as a function of time is typically described by an S-shaped curve, as shown in Figure 4.7. This concept is important in managing innovation and change and is often used to predict whether an emerging technology is likely to supplant an established one. Technology in this case can be defined as those tools, devices and knowledge that mediate inputs and outputs (process technology), or that create new products or services (product technology) [14].

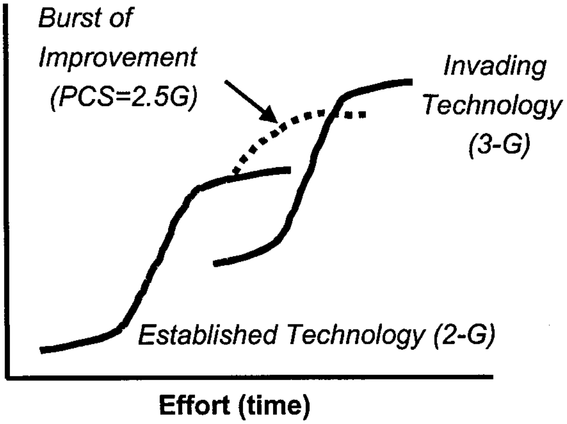

Figure 4.7 Technology S-curves, illustrating burst of improvement in performance of established technology triggered by invading technology

The S-curve suggests that the magnitude of performance improvement over a product's life cycle varies as the technology matures. In the early stages of a technology, the rate of progress in performance is relatively slow [15]. As the technology becomes better understood and developed, or competition forces more rapid development, the rate of improvement accelerates dramatically; this stage often corresponds to the emergence of a dominant design. The rate of improvement then eventually slows as the technology asymptotically approaches its practical limit. The essence of strategic technology management is to identify the inflection points and take appropriate actions. Failure to respond to such technological changes has forced many firms to exit from markets, and has provided a significant advantage to both market entrants and (existing) attacking firms [16].

The dashed line in Figure 4.7 indicates the manner in which established players often fight back with an additional 'burst of innovation' in the face of the uprising disruptive technology. However, these last breath efforts eventually run out of steam and the older technology is supplanted. Two examples of such bursts of innovation in the wireless communications industry are:

- the introduction of narrowband AMPS prior to the launch of digital time division multiple access (TDMA); and
- the current launching of many 2.5G ('PCS') services as an interim step between 2G and 3G wireless communications.

4.3 Case Study: The Evolution from 1G to 2G to 3G

The key findings of this study are presented in the following sections. The success strategies for 3G standards identified in Section 4.1 are derived from the statistical analysis of technical and market variables described earlier (see Figure 4.2); additional details of the analysis methodology are summarized in Appendix B to this chapter. The additional findings discussed in Section 4.2 draw on both the in-depth interviews and the industry survey. Section 4.3 focuses on the wireless industry value chain, and draws primarily on the results of the in-depth interviews.

4.3.1 Success Strategies for 3G and the Relationship to SDR

A surprising finding emerged from the statistical analysis of success factors of both 1G and 2G technologies in the wireless communications industry. In the competition between analog and digital standards, a very small number of market and technology factors has dominated. Figure 4.8 shows the potential magnitude of the influence of each of these factors on the market share gained by competing digital standards. The statistical analysis (see Appendix B) has been utilized in Figure 4.8 to assess the potential increase in the number of subscribers that could have been achieved by the major competing digital standards over the period 1993–1998. Based on these results, six very clear strategies emerge to steer the successful development

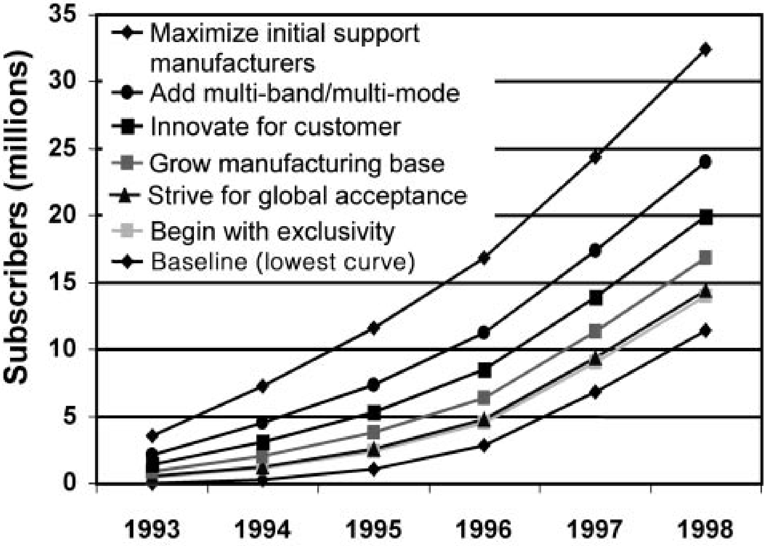

Figure 4.8 Six factors found to dominate the number of subscribers for competing digital standards

of any 3G wireless communications standard. These strategies can be closely related to potential advantages offered by SDR, pointing to its emergence as the dominant design.

4.3.1.1. Strategy #1: Maximize Initial Support

It is absolutely imperative to maximize the number of handset and equipment manufacturing companies who initially support the 3G standard. This initial support was found to have been the most significant factor in determining the success of competing digital standards, regardless of later growth in the number of supporting firms. In Figure 4.8, for example, the baseline digital standard could have almost tripled the subscriber base that it had achieved in 1998 by gaining the initial support of additional manufacturers.

The strategic implication of this finding is that a company's later competitive position will be vastly improved by organizing as broad as possible a base of industrial and government support for any single new standard rather than by forging ahead with a minimum number of sponsors.

In practice, such support may be difficult to achieve and another equally valid solution must be sought. Software defined radio can mitigate the impact of multiple standards and provide to end users and others the appearance of uniformity and technology transparency, thereby effectively broadening the base of support.

4.3.1.2. Strategy #2: Include Multiband and Multimode Capabilities

Multiband and multimode capabilities will be critical to the success of 3G standards. In North America, the early availability of dual-mode (800 MHz) TDMA/AMPS and CDMA/AMPS, if anything, prolonged the reliance of cellular customers on AMPS and slowed the market penetration of digital technologies. Compared to the overall world average as of the end of 1998, the US and Canada still lagged far behind in terms of digital penetration in the cellular marketplace, with 80% of subscribers still using AMPS. The introduction of dual-band 800 MHz/1900 MHz TDMA and CDMA capabilities did little to offer real value to cellular/PCS customers. In Europe, on the other hand, the introduction of a single digital technology (global system for mobile communications (GSM)) and the rapid phasing out of analog services provided GSM with the opportunity to promote multiband (900/1800/1900 MHz) handsets as an attractive 'world phone' solution to the international roaming problem. Europe, in stark contrast to the US, had already 'gone digital', with 90% of subscribers using GSM by 1998. The Asia-Pacific region, although more heterogeneous than Europe in terms of standards, was already predominantly digital, with PDC and GSM sharing the bulk of the subscriber market. In Figure 4.8, the baseline digital standard could have more than doubled the subscriber base that it had achieved in 1998 by introducing multiband/multimode handsets.

The strategic implication of this finding is that the competitive position of any new standard (and perhaps the coupling of the new standard with an existing standard) will be greatly strengthened by utilizing multiband/multimode capabilities to offer truly new features and services rather than focusing exclusively on backwards compatibility. This latter focus simply prolongs reliance on more entrenched, primitive technologies.

Software defined radio provides a means to support a fluid and dynamic combination of cellular bands and modes according to the needs of a particular geographic region, service provider, or end user. These combinations are often not known in advance, and the traditional approach precludes easy or economically acceptable solutions. Also included in SDR is the ability to develop new features and capabilities to meet the ever more sophisticated demands of business and consumer wireless customers.

4.3.1.3. Strategy #3: Maintain Rapid Technological Innovation – Focus on Consumers

Following introduction, rapid technological innovation in consumer equipment is a key competitive advantage for wireless standards. The corresponding factor utilized in this study to represent the rate of technological innovation was the rate of increase in handset talk-time/weight ratio. A very clear demonstration of the importance of such innovation is the overwhelming influence that it was found to have on the rapid deployment of PHS systems in Japan. PHS was able to offer subscribers very small, lightweight, and feature-rich handsets, with the result that PHS services became wildly popular in Japan and other Asian countries. It is important to note that technological innovation will be transparent to the end user if it is principally related to the requirements of the network operator, as has been a great deal of digital technology. In Figure 4.8, the baseline digital standard could have almost doubled the subscriber base that it had achieved in 1998 by matching state-of-the-art innovation in cellular handset performance.

The strategic implication of this finding is that the competitive position of any new 3G standard will be greatly strengthened by focusing technological development on offering new features and services that directly impact the end user.

Software defined radio supports the offering of new features and services by providing a dynamic platform that can offer application and service flexibility in conjunction with transparency of the underlying air interface technology.

4.3.1.4. Strategy #4: Rapidly Increase the Manufacturing Base of Support

It is critical to increase as fast as possible the number of companies who support any new 3G standard. If, for example, CDMA does indeed achieve the forecast dominance over TDMA, it will be due in great part to the successful attraction of a substantially larger base of support. The relative sizes of the respective support camps for the dominant digital standards in 1998 was estimated from the memberships of the CDMA Development Group (CDG) (numbering 96 members as of March 1998) and the Universal Wireless Communications Consortium (UWCC) (numbering 72 members as of March 1998). On the other hand, the GSM MoU Association, which represents the GSM industry worldwide, numbered 251 members as of March 1998. In Figure 4.8, the baseline digital standard could have increased by 50% the subscriber base that it had achieved in 1998 by increasing more rapidly the number of manufacturers supporting the standard.

The strategic implication of this finding is that the competitive position of any new standard will be greatly strengthened by every effort that is undertaken to expand the number and presence of supporters throughout the industry.

Software defined radio allows new entrants and incumbent suppliers to add one or more 3G standards to any air interface standards that they may already support. Software defined radio provides a path for vendors to reduce the number of unique air interface combinations that they must support via different product models. By offering a flexible evolutionary path from

2G to 3G, SDR also has the potential to broaden the user base and hasten overall acceptance of 3G standards.

4.3.1.5. Strategy #5: Strive for Global Acceptance

It is important to have any new 3G standard adopted in as many major international regions as possible. Regional standards, such as PDC and PHS, and perhaps even still TDMA and CDMA to some degree, stand to be eventually displaced in the wireless communications market by standards offering global portability. The continuing success of GSM, which is the only standard with a significant presence in all major markets worldwide, attests to this fact. In Figure 4.8, the baseline digital standard could have increased by at least 25% the subscriber base that it had achieved in 1998 by gaining commercial acceptance in additional regions throughout the world.

The strategic implication of this finding is that the competitive position of any new 3G standard will ultimately depend on the ability with which sponsoring organizations are able to influence international standards and regulatory debates, and international partnerings and alliances, and adoption by network operators throughout the world.

Software defined radio is a solution that can act as a unifying force across disparate technologies. It can remove decision uncertainty about deployment of a particular technology; as SDR becomes a pervasive core technology, the selection of any particular standard becomes less of an issue.

4.3.1.6. Strategy #6: Begin with Exclusive Adoption in a Major Region

Although international adoption is the ultimate goal, this study has clearly identified the competitive advantage to be gained for any new 3G standard by achieving exclusive adoption of the standard in a major international market region. The initial success of AMPS in North America, and later of GSM in Europe, as well as PDC and PHS in Japan, all attest to this fact. In Figure 4.8, the baseline digital standard could have increased by at least 25% the subscriber base that it had achieved in 1998 by initially gaining exclusive adoption in one major region.

The strategic implication of this finding is that the early sponsoring organizations of any new standard must also strive to influence local standards and regulatory debates, and to set up suitable local partnerings and alliances, so as to initially carve out an exclusive position at least in the their own home region. This local stronghold may very well prove to be of great strategic importance in the transition toward 3G wireless standards.

However, the capabilities and advantages of SDR as a dominant design may obviate the need for any local adoption stronghold to be established for 3G standards.

4.3.2 Additional Findings

There was a strong consensus among industry experts that a single standard was unlikely to emerge from the IMT-2000 process. On the other hand, it was felt that the number of globally accepted digital standards would likely be reduced to three, or perhaps two. These results are shown in Figure 4.9. Subsequent developments revealed the emergence of three strong camps, each promoting the development of an IMT-2000-compliant but backwards compatible variant of one of the three existing digital standards (GSM, TDMA, and CDMA):

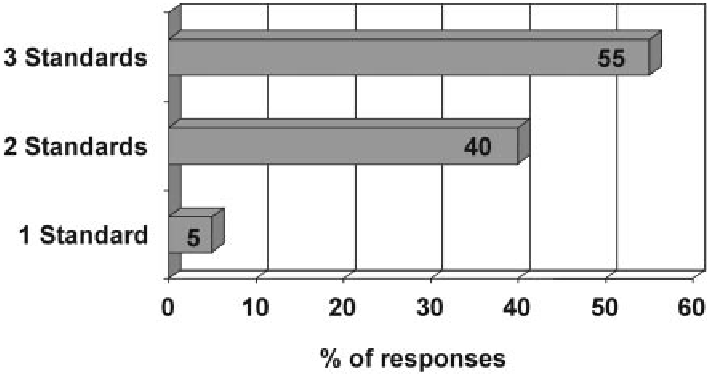

Figure 4.9 Questionnaire responses: "What do you think will happen in the wireless industry with regards to the proliferation of new technologies and competing air interfaces?"

- Universal Mobile Telecommunications Service (UMTS) – GSM based
- Universal Wireless Communications Consortium (UWCC) – TDMA based
- Wideband cdmaOne Alliance – CDMA Development Group (CDG) – CDMA based

Since 1998, the first two of these camps have aligned, giving rise to two competing 3G standards efforts (now known as 3GPP and 3GPP2). Industry experts overwhelmingly indicated that the 3G standards process would substantially reduce the number of worldwide wireless standards.

Wireless industry participants ranked multiple air interface capabilities as the most important design elements in terms of determining the commercial evolution of SDR-based handset technologies and products, as shown in Figure 4.10.

Due to their emergence from the collision of the cellular phone and PDA/PC industries, SDR devices and services are regarded as a potentially disruptive innovation. This collision is already creating both market turbulence and new market opportunities, for both incumbent firms and new entrants.

Software defined radio technologies were perceived to be an extremely powerful tool for wireless service providers to offer their subscribers many attractive new value added services. Software-defined-radio-based mobile devices were also perceived to be an extremely lucrative opportunity for traditional manufacturers of handheld PCs and PDAs to expand into the wireless communications market. These two perceptions may prove to be critical in accelerating the development of SDR, given that the first signs of weakening PC demand and flattening cellular service revenues were already appearing in 1998.

Another key finding was that SDR itself was not widely perceived to be a wireless appliance or network *standard*, but rather a potential *design element* or set of design elements to be incorporated into a future standard or standards.

The growth of SDR handsets was expected to be dependent on how quickly they can penetrate into both wireless phone and PC/PDA markets. The expectations of industry participants for the future penetration of SDR handsets into the wireless handset and PDA/handheld PC markets indicated that SDR appliances were expected to penetrate the wireless phone

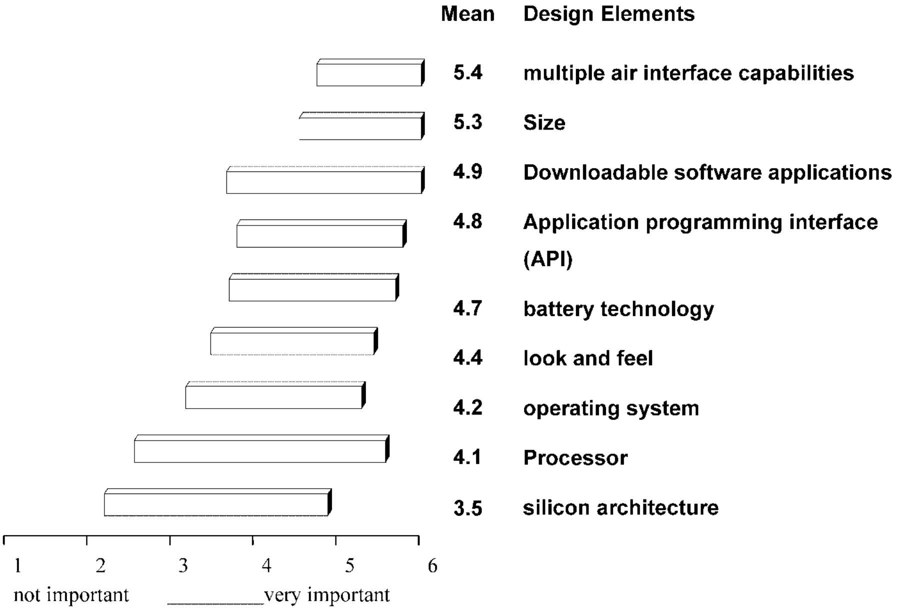

Figure 4.10 Ranking in importance of software phone design elements (the range of responses is also indicated)

market more quickly than the PDA market, with a 75% market penetration expected into the former by the year 2006. In the PDA market, SDR appliances were predicted to reach 60% market penetration by the year 2006.

4.3.3 Support for SDR Varies Across the Value Chain

Industry experts were asked several questions related to current and future support for SDR within the wireless industry. These questions were framed in terms of the wireless industry value chain. The results are presented in Figure 4.11.

The value chain links showing the greatest disparities between current support and perceived necessary support were the service providers, application developers, and end users. Equipment manufacturers and government/regulatory agencies were expected to have the greatest influence on future standards development.

4.4 SDR as the New Dominant Design: an Industry Framework

4.4.1 Factors Influencing Dominance

Many factors interact at the same time to determine dominance of a specific technology or design. This section presents an integrated framework within which players in the wireless industry can better assess the potential impact of their strategic and tactical efforts to influence the emergence of SDR as the dominant design. Conceptually, however, it is helpful to classify the different scenarios where dominant processes unfold:

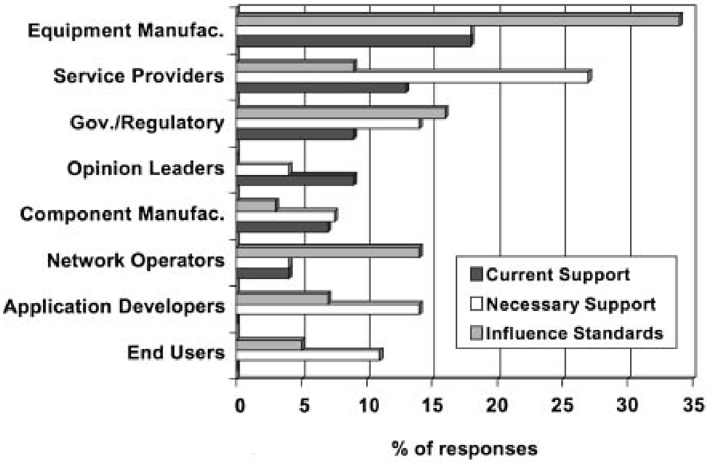

Figure 4.11 Questionnaire responses: "Who is actively supporting SDR today in the global wireless industry?"; "Who would have to actively support SDR in order for the technology to achieve global acceptance?"; "Who do you think will have the most influence on the further evolution of international wireless standards?"

- market competition involving products embodying unsponsored standards, where no players in the market have proprietary interests in any of the relevant competing technologies;
- market competition among sponsored (proprietary) standards, where firms fight to impose their own proprietary standards;
- agreements within voluntary standards-writing organizations, where all or the main players agree upon a specific technology;
- direct government promulgation/intervention, where the government makes the final decision about which technology to accept.

Any integrative framework should build upon the existing management literature, and fulfill at least two goals. First, provide a complete but sparing list of factors that affect dominance. Second, provide an indication of the conditions under which each factor will have a stronger or weaker effect on the final result of the dominance battle. The framework provided below [17] tries to address both points.

The following factors can be considered to affect the likelihood of dominance of a specific technology in the market. No factor by itself tends to have enough power to tilt the balance in favor of a specific technology. Rather, the end result is the outcome of the interplay among all the factors:

- technological superiority
- firm's assets and credibility
- firm's strategic maneuvering:
  - entry timing
  - pricing and communications
  - alliances and sponsorships
  - provision of complementary products and systems

- government intervention
- relative size of the installed base

Technological superiority captures the pure effect of technology, e.g. how a specific technology performs *vis-à-vis* competing alternatives. Other things being equal, the better a technology is, the higher the likelihood that it will become dominant. The combination of a firm's assets and credibility captures what has been termed 'complementary assets', e.g. those assets that are necessary for a firm to benefit from (read impose) its technological innovation. These assets may be crucial when battling for dominance, as the well-known case of IBM and the Apple Macintosh illustrates.

A firm's strategic maneuvering captures the key elements of strategy open to a firm when it comes to promote its technology to be the dominant one. Four elements are of particular importance: the timing of entry to the market (launching of the product); the specific pricing and communications strategy that the firm follows to introduce and promote its technology in the market; the firm's strategy with respect to alliances and sponsorships (including licensing) to favor its technology; and the ability of a firm to secure the provision of products and systems complementary to its technology.

Government intervention captures the role of the government as a regulator and arbitrator of competing technologies; in some cases, it is the government which finally decides which technology will dominate.

The last factor, relative size of the installed base, captures the pure effect of 'network externalities'. Even though it could be considered a variable resulting from the interplay of all the other variables, modern economic theory tells us that the dynamics of network externalities produce a self-reinforcing loop which associates greater relative size of installed base with the rate of adoption of a specific technology. In other words, the size of the installed base provides an 'extra push' to the chances of dominance of a specific technology, on top of the specific effect of the previous variables.

Each of these factors is expected to have a different effect depending on the stage of the dominance process in which a market finds itself, as summarized in Figure 4.12. Consider an industry in which a battle for dominance will emerge. The beginning of the industry can be considered to be at time t_0, when a pioneer firm starts doing applied R&D aimed at producing the product in question (e.g. digital cellular phones, which are supplanting analog phones in the wireless communications marketplace). As other studies have shown, other firms soon follow the first one, and a virtual 'development race' begins.

The next milestone in the dominance process is the launching of the first commercial product (t_L in Figure 4.12), which for the first time directly connects a product coming out of the lab's ideas with customers and other market agents. The first commercial launching triggers a whole new set of dynamics in the industry's dominance battle, and therefore it is a key event that all players watch carefully.

Finally, at some point in time, a specific technology achieves dominance over competing ones. Different researchers have termed this differently, in particular 'dominant design' or 'standard'. The broader notion of 'dominance' is used here to refer to both concepts: the fundamental idea in both dominant designs and standards is that a given technological approach achieves dominance over competing alternatives. In Figure 4.12, t_D denotes the time of emergence of a dominant alternative.

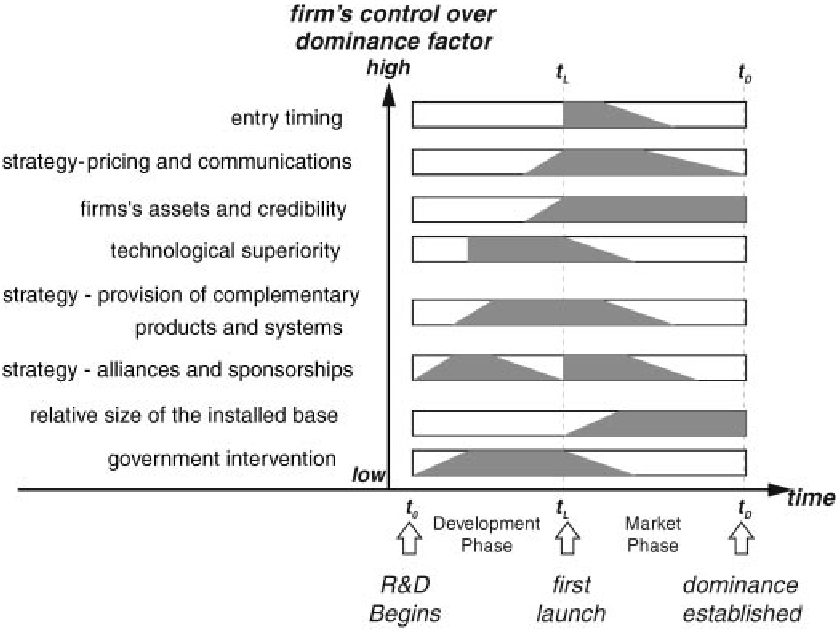

Figure 4.12 A firm's control, as a function of time, over factors influencing dominance

Each dominance factor has also been ranked by the degree of control (high to low) that a firm has over it. Some factors are directly controlled by a firm (e.g. pricing strategy), whereas there are factors over which a firm has little, if any, control (e.g. government intervention). Even though the specific order in the figure is somewhat arbitrary, it does convey the important message that a firm has different degrees of control over the many variables that influence its likelihood of winning the dominance battle.

Moreover, the effect of each variable is not the same throughout the industry timeline. Only a correct understanding of these issues will allow the firm to focus on the right dominance variables at the right time. In particular:

Strategy entry timing. Other things equal, maximum effect on achieving dominance will occur when the firm is the first to launch a commercial product (that is, t_i, the launch date for firm i, $=t_{\mathrm{L}}$). Close followers will not affect significantly its chances of success. However, later entry will seriously reduce a firm's likelihood of dominance.

Strategy pricing and communications. Pre-announcements just prior to the first commercial launching and an aggressive pricing strategy may increase a firm's likelihood of dominance. However, the relative importance of this effect will diminish after launching, as other factors of dominance start to predominate.

Firm's *assets and credibility*. Even though it is not important during the development phase, the assets and credibility of a firm will be crucial during the market phase, as well as during the pre-announcement phase before the first launch.

Technological superiority. This dominance factor can have its greatest effect during the last segments of the development phase, when firms have a more concrete technology portfolio to use as a base for negotiation and persuasion for alignment. For instance, in part because of their superior technology, Sony and Philips were able to align several firms around their CD technology before the commercial launch. At that time, both firms were recognized as leaders in technological development of CDs. Soon after launching, though, technology variables rapidly lose importance to other variables in the quest for dominance, as the examples of VCR and PCs show.

Strategy provision of complementary products and systems. Firms often seek to align suppliers of complementary products well before the launching of the first commercial product. In the wireless communications industry today, for example, both traditional cellphone manufacturers and potential new entrants from the handheld computer industry are aggressively trying to align suppliers of operating system components and value added services and applications prior to introducing the next generation of user terminals. Soon after the first launch, however, many key competitors will also have introduced their own products and forged their own alliances with suppliers of complementary products, and therefore the effect that this strategy can have on the dominance battle tails off.

Strategy alliances and sponsorships. There are two types of alliances/sponsorships that are important for dominance: technology-oriented and market-oriented. The timing for each is also different. Technology alliances can strengthen the credibility and performance of a competing alternative. These alliances often happen somewhere between t_0 and t_L – when a firm's technological approach can already show its potential but – obviously – before it has been completely developed. Market alliances tend to happen right after – or even before in some cases – the launching of the first commercial product in the industry.

Relative size of the installed base. This variable captures the pure effect of network externalities, and its increasing effect on dominance will start to be present soon after the launching of the first commercial product.

Government intervention. The effect of government intervention on dominance is often strongest in the second half of the development period, where firms have developed their technological alternatives to a point where the government can make an informed decision regarding specific purchases or specific targets for industry regulation. Via such decisions, governments can effectively trigger the dominance of a specific technology among competing ones. After products are launched in the market, government effect on dominance tends to vanish as market forces prevail.

4.4.2 Discussion: Dominance and SDR

By simultaneously examining Figures 4.8, 4.11, and 4.12, a consistent picture can be painted which provides deep insight into the dynamics of an industry poised for the emergence of a new dominant design. The lessons learned from a careful examination of the details found in this picture offer several strategic insights for those companies choosing to enter the industry and to those market incumbents who have no choice but to adapt, compete successfully, or exit the industry.

Of the six factors found to influence the outcome of the battle between competing digital wireless standards (Figure 4.8), the second most important – adding multiband and multimode capabilities to wireless phones – corresponds to the emergence already of one key architectural element of SDR devices as the dominant design platform. The remaining design elements are expected to emerge as SDR devices continue to evolve.

The remaining five factors presented in Figure 4.8 can be mapped onto the dominance factors listed in Figure 4.12, as shown in Table 4.1. It is the timing of each factor – in terms of its ability to influence the outcome of a pending dominance battle – that emerges as the parameter that has determined its importance in influencing the dynamics of the wireless industry. Figure 4.11 drives this point home by revealing that the three wireless industry value chain links most empowered to wield early influence according to Figure 4.12 – equipment manufacturers, government/regulatory agencies, and network operators – are the ones broadly identified as having the greatest power to influence future standards development.

Table 4.1 Alignment of dominance factors from Figure 4.12 with technology and market factors from Figure 4.8

Dominance factors from Figure 4.12	Market and technology factors from Figure 4.8
Maximize initial support	Alliances and sponsorships Government intervention Provision of complementary products and systems
Innovate for customer	Technological superiority
Grow manufacturing base	Technological superiority Firm's assets and credibility Relative size of the installed base
Strive for global acceptance	Relative size of the installed base Alliances and sponsorships Government intervention
Begin with exclusivity	Entry timing Government intervention

4.5 Standards, Regulatory, and Trial System Initiatives

4.5.1 SDR: Vision and Commercial Timeline

As mobile communications networks evolve to accommodate accelerating demand for wireless voice and data services, equipment manufacturers and network operators are being forced to confront many difficult, and simultaneous, challenges. These challenges include supporting explosive subscriber growth using multiple standards, modes, and frequencies, stemming the proliferation of equipment and service platforms, meeting the demand for wireless Internet and information services, supporting the higher cost and longer lifetime of 3G terminals, adapting to the growing pace of competition and consolidation, and overcoming the cost and scarcity of wireless spectrum. In the face of these challenges, SDR offers the wireless industry an alternative vision wherein every consumer has a personalized device which works everywhere, system operators have future proof networks, manufacturers service a mass customized market with one product platform, consumers have new services instantly downloaded to a single device, and network operators achieve nationwide and global network footprints independent of air interface.

Software is already replacing hardware in the wireless equipment manufacturing process to consolidate product platforms and to increase their flexibility (see Figure 4.13). Many manufacturers already support some reprogramming of base station functions and configurations in the field, albeit over proprietary network interfaces. In handsets, on the other hand, this software is not yet widely designed to support reprogramming after the manufacturing process is complete. Driven by the growing needs of network operators to support more advanced management of deployed handsets (provisioning, repairs, upgrades, personalization, and multimode roaming), SDR capabilities will soon be expanded to support software download – including over-the-air downloads – and reconfiguration of user terminals. In the long run, SDR also offers promise as a key technology, which, in conjunction with sound spectrum management policies, can enable higher subscriber densities, more flexible service offerings, and more efficient use of available spectrum in wireless networks.

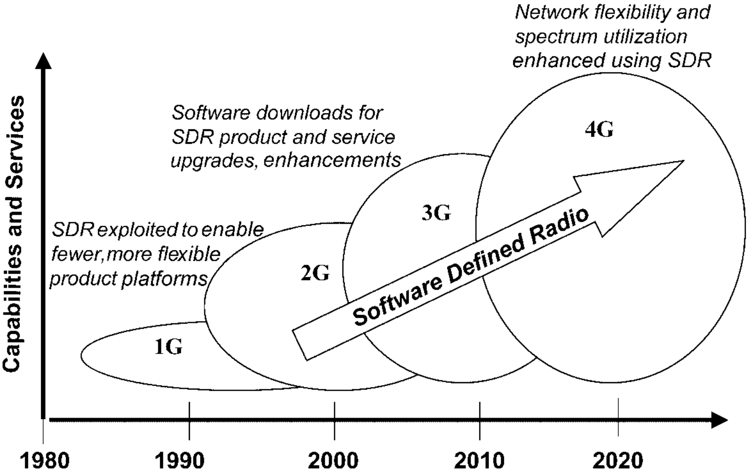

Figure 4.13 SDR timeline

Underlying all of these benefits are three essential product capabilities, enabled by SDR technology (see Figure 4.14). The first element, and the element most commonly associated with SDR, is the ability of products to support multiple and simultaneous modes and bands – both cellular and non-cellular. The second element of SDR product capability is a powerful and flexible application execution environment. The third element is the ability for a device to be reprogrammed, and to support secure and reliable software download. Ultimately, the relative superiority of a particular SDR product architecture will depend on many additional parameters, including product cost, product size, power dissipation, design re-use, and the ease of software development and maintenance.

4.5.2 The Drive for Open Architectures

SDR has been recognized as a key element in the evolution of commercial, defense, and civil government mobile communication capabilities. However, there are several fundamental differences across these different application domains that naturally drive some divergence in the degree of 'openness' in the SDR architectures being developed. This divergence was

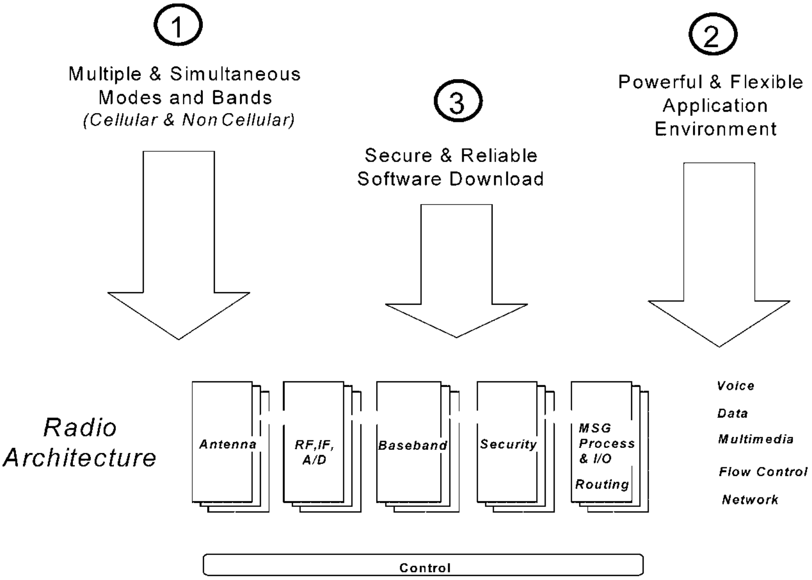

Figure 4.14 Three essential elements of SDR (source: SDR Forum Technical Report 2.1, November 1999)

the subject of a Joint Experts Workshop on Open Architecture sponsored by the SDR Forum (Atlanta, Georgia, February 2001) which included a series of related presentations from both the government and commercial wireless communities.

The drive for open equipment architectures in government/military stems from the fact that as many as 30–40 legacy military air interfaces must be supported, many of which are proprietary. As a result, there will always be fewer players and less competition, leading to higher costs of production. Furthermore, the majority of military infrastructure is not fixed, but rather must be fielded in mobile network scenarios.

In the commercial world, multimode SDR equipment will, from a practical standpoint, only be required to support three to four air interfaces, and these air interfaces are developed via open standards processes. Proprietary equipment implementations are thus the norm, which has led to a much larger number of players, a greater degree of competition and a faster pace of innovation, and much lower equipment costs. Also, the commercial SDR task is simplified due to the fact that most of the infrastructure is fixed.

A key foundation of the SDR Forum's technical working group activities thus continues to be developing common enabling technologies to address those problem areas that are similar across different application domains. These common enabling technologies include middleware (Java, Corba), efficient and secure software download (MExE, WAP, OTAR, …), authentication, protocol stacks (TCP, IP, SNMP, HTTP, OSPF, …), end-to-end technology integration, (RF/baseband, network, applications, …), validation, and industry trial systems/ test beds.

A key SDR Forum initiative launched in 2001 is focusing on coordinating the development of wireless industry trial systems, in order to:

- clearly identify those network operator requirements that can be supported using SDR technologies;
- clarify and accelerate timelines for commercial adoption of various SDR technologies;
- integrate and showcase those SDR technologies that support network operator requirements, as they become commercially available.

4.5.3 Standards and Regulatory Drivers for SDR

The wireless industry has experienced a recent flurry of standards and regulatory activities focused on SDR, driving home the urgency with which SDR solutions are being sought. In addition to their technology leadership, the SDR Forum has also played an active role in driving several key standards and regulatory initiatives.

Working closely with the Federal Communications Commission (FCC) and international regulatory bodies, the SDR Forum's Regulatory Committee has helped coordinate activities leading to the FCC's issue of a Notice of Inquiry (NOI) [18] on SDR in March 2000. As a result of the very enthusiastic response to this NOI by major wireless equipment manufacturers and network operators, the FCC released an initial Notice of Proposed Rules Making (NPRM) [19] on SDR in December 2000. Two key proposals presented in this NPRM are:

- Changes in radio functionality in SDR equipment (frequency, power, modulation type) would be authorized under a new class of permissive changes, Class III.
- SDR equipment would be authorized to use 'electronic labeling', in order to provide a method to relabel equipment in the field following any changes to previously approved devices.
- This streamlining of the equipment approval process would remove key potential regulatory hurdles to the further development and deployment of SDR equipment and systems.

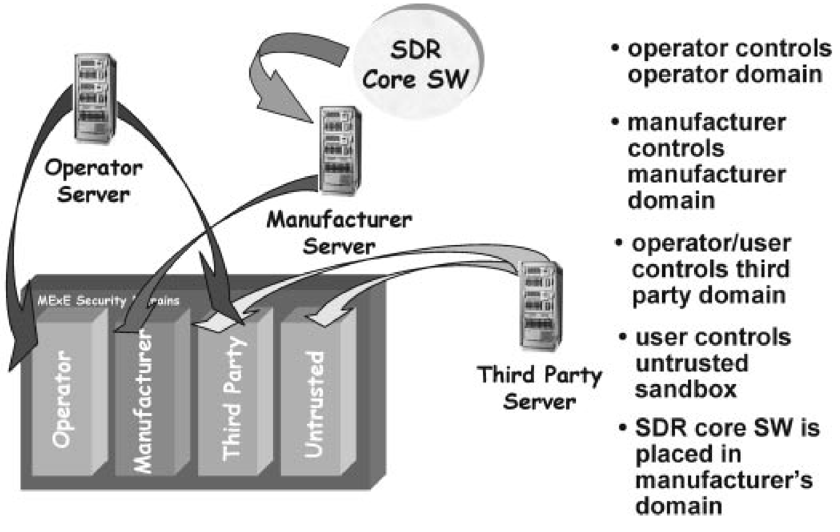

Figure 4.15 SDR core software download (as incorporated into 3GPP-MExE Release 2000)

Over the past 2 years, the SDR Forum's Software Download Task Group has established a formal liaison with the Third Generation Partnership Project's (3GPP's) Mobile Application Execution Environment (MExE) standards group [20], in order to help define and standardize those SDR capabilities most critical to the commercialization of reconfigurable wireless handsets and other advanced mobile user terminals. In August 2000, basic SDR capabilities were submitted for incorporation in MExE's year 2000 standards release, and were ratified at the 3GPP annual meeting in Bangkok, December 2000. These additions to the 3GPP standards explicitly enable core radio software download and terminal reconfiguration (see Figure 4.15), clearing the way for equipment manufacturers and network operators to begin finalizing requirements and terms for volume introductions of SDR terminals, perhaps as early as 2002–2003. Strong interest has already been registered by network operators to exploit such capabilities for a growing number of terminal management challenges.

4.6 Conclusions

This chapter has sought to demonstrate the analytical basis for the thesis that SDR is destined to emerge as the dominant design in the commercial wireless industry as it transitions into the world of 3G. The interplay between technology and markets is a complex one, but one that can be approached scientifically. The results of the research and statistical analysis reported herein describe the quantitative relationships between influencing factors, a complement to the widespread intuitive speculation regarding the future of SDR and 3G. The relationships between such factors and possible market strategies have been described, providing direction to market players across the value chain. This has also provided direction to the SDR Forum in establishing its own strategy, with regard to standards, regulation and trials, to see SDR emerge as the dominant design.

Appendix A. Market Study – The Variables

Names and descriptions of variables for which data were assembled and analyzed.

Variable	Description
Numbers of subscribers and subscriber market share	
AnSUBSCRIBE	Total number of analog cellular telephone subscribers worldwide
DigSUBSCRIBE	Total worldwide digital cellular telephone subscribers worldwide
$\sum$-SUBSCRIBE	Total number of cellular telephone subscribers worldwide (AnSUBSCRIBE + DigSUBSCRIBE)
SUBSCRIBE	Number of subscribers for each standard
ΔSUBSCRIBE	Quarterly change in 'SUBSCRIBE'
MktShr	Share of total (i.e. analog + digital) subscriber market for each standard
ΔMktShr	Quarterly change in 'MktShr'
AnMktShr	Share of analog subscriber market for each analog standard
ΔAnMktShr	Quarterly change in 'AnMktShr'
DigMktShr	Share of digital subscriber market for each digital standard
ΔDigMktShr	Quarterly change in 'DigMktShr'

(*continued*)

Variable	Description
Regional adoption of standards	
EXCLUSIVE	Number of major regions in which each standard is the only analog or digital standard in use
REGION	Number of major regions in which each standard is in use (0–6)
REGION(t2)	'REGION', delayed by two quarters
	Handset and infrastructure equipment manufacturers
HS-MajCo	Number of major manufacturers introducing new handset models. The eight major companies are: Motorola, Ericsson, Nortel, Alcatel, AT&T/Lucent, Siemens, Nokia, and Qualcomm
EQ-MajCo	Number of major manufacturers completing infrastructure equipment installations
∑-MajCo	Sum of HS-MajCo and EQ-MajCo
HS-MANUFAC	Total number of manufacturers introducing new handset models
EQ-MANUFAC	Total number of manufacturers completing infrastructure equipment installations
MANUFAC	Sum of HS-MANUFAC and EQ-MANUFAC
MANUFAC(t4)	MANUFAC, delayed by four quarters
INITIAL[a]	Number of companies initially supporting each standard (companies introducing new handset models or completing infrastructure equipment installations for each standard within first six quarters of service launch)
NTWK	Number of networks completed
BASE-STN	Number of base stations installed
Government support	
GovSupStan[a]	Government support for standards development (0 or 1)
GovSupTech[a]	Government support for technology development (0 or 1)
GovSup[a]	Government support for standards or technology development (0 or 1)
	Technological superiority and rate of technological innovation
SpecEff[a]	Spectral efficiency of each standard (calls per cell per MHz)
HS-TkWt	Average talk-time/weight ratio of all handsets introduced each quarter for each standard (min/g)
INNOVATE[a]	Rate of change of average talk-to-weight ratio of handsets for each standard (min/g per quarter)
MODELS	Number of new handset models introduced during each quarter
MULTIBAND	Availability of multiband handsets incorporating each standard (0 or 1)
MULTIMODE	Availability of multimode handsets incorporating each standard (0 or 1)
MM/MB	Sum of MULTIBAND and MULTIMODE (0, 1, or 2)
MM-AMPS	If MULTIMODE = 1, other modes include AMPS (0 or 1)
MM-GSM	If MULTIMODE = 1, other modes include GSM (0 or 1)
MM-TDMA	If MULTIMODE = 1, other modes include TDMA (0 or 1)
MM-CDMA	If MULTIMODE = 1, other modes include CDMA (0 or 1)

[a] Variable assumes constant value for each standard throughout entire period.

Appendix B. Market Study – The Statistical Analyses

The table below lists those variables that emerged as being statistically significant following regression analyses. All significant pair-wise correlations were eliminated from the models.

Variables	Description	Rational	Significance
SUBSCRIBE (dependent)	Number of subscribers worldwide for each standard	Fundamental dependent variable	Both analog and digital standards
EXCLUSIVE	Number of major regions in which each standard is the single analog or digital standard in use	Indicative of ability of standard to achieve regional dominance	Digital standards only
REGION	Number of major regions in which each standard is in use	Indicative of ability of each standard to achieve global dominance	Both analog and digital standards
MANUFAC	Total number of companies introducing new handset models or completing infrastructure equipment installations	Indicative of manufacturing support achieved by each standard	Both analog and digital standards
INITIAL	Number of companies initially supporting each standard	Indicative of manufacturing support already in place for each standard at time of launch	Digital standards only
INNOVATE	Rate of change of average talk-to-weight ration of handsets for each standard (min/g per quarter)	Indicative of the influence of the pace of technological development for each standard	Both analog and digital standards
MM/MB	Availability of multiband or multimode handsets incorporating each standard	Indicative of the influence of the availability of multimode and multiband technologies	Both analog and digital standards

Separate analyses were carried out for analog and digital standards. Models were tested based on a variety of dependent variables, including absolute numbers of subscribers, quarterly changes in numbers of subscribers, market shares, and quarterly changes in market shares. Each regression model combined the relevant sets of data for all (analog or digital) standards, in order to assess the overall dependence of the selected group of predictor variables. The most statistically significant models were built utilizing absolute subscriber numbers as the dependent variable. Residual analysis [21] was also carried out in order to verify the validity of the regression analyses. For each regression model, *standardized residuals* were plotted both as a function of the predicted values of the dependent variable and as a function of time. Further details of the regression analyses are presented elsewhere [1].

The results presented in Figure 4.8 utilize the regression coefficients extracted from the above analyses, and assume the following changes in the six independent variables with respect to the baseline case:

INITIAL: +10 (i.e. increase by 10 the number of handset or infrastructure equipment manufacturers who supported the standard at time of launch)

MM/MB: +2 (i.e. add multiband and multimode capabilities to handsets)

INNOVATE: +0.05 min/g per fiscal quarter (i.e. roughly doubling the average rate of technological innovation)

MANUFAC: +10 (i.e. add the support of 10 more handset or infrastructure equipment manufacturers over the period studied, 1993–1998)

REGION: +2 (i.e. add two major regions using the standard)

EXCLUSIVE: +1 (i.e. add one major region in which the standard is used exclusively)

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5

Software Radio: The User Dimension

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New technology development is frequently undertaken on a technology-led basis, at least in its early stages. Increasingly, however, and particularly with respect to technologies which promise to impact major existing markets, new approaches are being employed to validate implicit assumptions and thence more effectively direct future technology research. This chapter describes one such approach, which has been applied to understand consumer perspectives and implications of software defined radio technology within the context of the mobile telecommunications market. Bringing together techniques from human factors research and marketing, we describe a methodology of potentially wider relevance, as well as providing scenarios and storyboards for some illustrative end user applications.

5.1 User Requirements for 'Future' Technology

Software radio (or software defined radio, SDR) is anticipated to be the next major leap forward in mobile and wireless communications [1] and is seen as an essential component of future third- (3G) and fourth-generation (4G) mobile communication systems. This technology will provide an even greater degree of flexibility to the end user and other stakeholders involved in its deployment. For example, it has been suggested that clear benefits can be derived from the application of reconfigurable radio techniques in handset design, particularly in the potential to support multiple air interface standards. There are a number of proposed advantages for the end user, including enhanced roaming capabilities and selection of the most attractive network to meet the user's preferences [2]. However, hand in hand with this flexibility comes increased complexity and choice. There are likely to be many unique challenges for the designers of the user interaction and user interfaces for future software radio devices. Given that the enabling technologies required for software radio are developing rapidly, it is crucial that detailed user requirements work is carried out while the technology is still being developed. Users' requirements need to be understood very early on, not just the immediate requirements of end users themselves, but also those of all system stakeholders such as manufacturers, network operators, and service providers.

5.1.1 Benefits of User-centered Design

The value of a user-centered design process, together with supporting tools and techniques (broadly illustrated in Figure 5.1), is well recognized in the development of computer-based systems. Such a design process analyzes user needs by eliciting requirements directly from users, and considers the impact of emerging designs upon those needs. Prototype systems can be developed and evaluated with real users, in an iterative fashion throughout the design life cycle, providing a means of refining and validating the initial user requirements. To some extent, this approach has been adopted for the development of today's communication technologies, see, e.g. Refs. [3–6]. Human Factors researchers have developed numerous user-centered design methods and tools to support this process, e.g. Participatory Design [7], Contextual Design [8], and Scenario-based Design [9]. A user-centered approach can thus add significant value to the research and development of products embodying software radio by reducing the risk of developing technology-driven products and systems that may not meet the real needs of the users, or for which there are no appropriate business models or feasible stakeholder relationships.

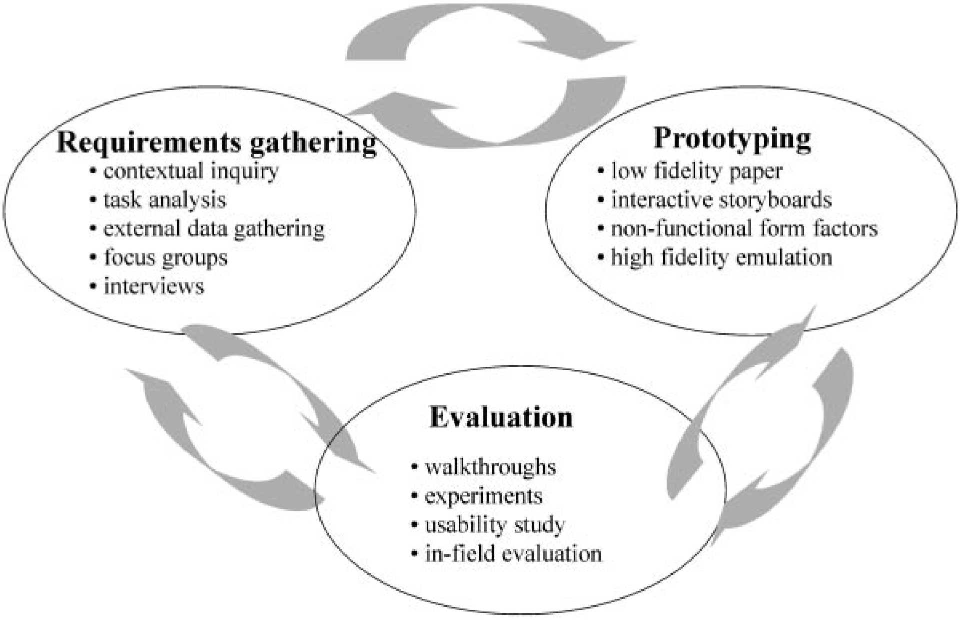

Figure 5.1 User-centered design

To date, there has been little work specifically addressing what software reconfigurable radio systems will mean for end users. However, given that the enabling technologies required for reconfiguration are developing rapidly, it is vital that the technologists working on this topic are provided with real insights into the key areas that need to be addressed if such systems are to meet the needs of future users. These insights will also help to avoid the potential risk of overwhelming users with unnecessary complexity. One of the first research initiatives to adopt such a user-centered approach was the European IST research project TRUST – Transparently Reconfigurable UbiquitouS Terminals – [10], which aimed to identify user requirements not just for the end user, but for network operators as well.[1]

5.1.2 The 'Non-existence' Problem

Whilst a user-centered approach within the design cycle of a computer-based system is fairly well prescribed, the use of such techniques within a research project aiming to define a future technology is prone to the 'non-existence' problem; that is, it is hard to get users to provide requirements for theoretical systems and functionalities. Coupled with this problem is the challenge of gathering user requirements for a system not to be used by a fairly homogenous user group, but for devices that could in fact be used by anyone, for a myriad of different purposes. These users are likely to vary immensely in their technical skills and comfort with technology. In a more typical example of user-centered design, say, of a new computerized system for a distribution company, it would be possible to observe users in their current activities, interview them, conduct task analyses, propose possible design solutions, and evaluate early prototypes with the future users of the new system. In this way, early user requirements can be formulated and refined, and passed to the system developers. Future skill requirements of the work force can also be described, and the training required for using the new system effectively can be formulated. Contrast this with the situation in which researchers of software radio find themselves:

- there are no comparable systems today: this is not incremental design;
- the technology is potentially extremely complex, and difficult to describe;
- there are no prototype implementations;
- software radio may impact all mobile communication users; it is not intended for use just by highly skilled specialists;
- the technology is not being designed for use in discrete well-defined professional applications, but rather for widespread everyday use by consumers.

We are trying to establish user requirements for a technology that will follow the introduction of 3G systems, yet those systems themselves are only just entering the mass market at the current time. Users' current and future needs will impact on the acceptability of 3G systems, which in turn will create new needs and expectations. This is known as the 'task-artefact' cycle [11].

A good example of this is the wired and mobile Internet. How could it be possible to explain to future mobile users of the Internet how these devices might work, and ask them to describe their requirements for such systems if they did not already have experience of both mobile phones and wired Internet access? Indeed, user experience with the wired Internet in no small way contributed to the disappointments experienced with the launch of wireless application protocol (WAP) mobile phones – user expectations had been based upon their much richer experience of the wired Internet. Early adopters of WAP technology thus

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[1] The impact of software radio upon network operators is discussed in Chapter 6.

expected the same performance and ease of access to the Internet to be coupled with the convenience of their mobile phone. Unfortunately early WAP systems (pre-general packet radio services (pre-GPRS)) failed to live up to such high expectations.

To consider a contrasting example, the overwhelming success of the global system for mobile communications (GSM) short messaging service has created a new need for tools to enable fast textual input for instant messaging. Undoubtedly future multimedia messaging applications enabled by 3G technology will create needs for alternative new ways of interacting with devices.

Table 5.1 gives examples of today's mobile and wireless usage, showing relationships between users, technology and activities.

Table 5.1 Example mobile and wireless usage [2]

User	Technology	Tasks
Teenager	GSM voice, GSM SMS	Social organizing, gossiping, jokes, shopping
Parent	Two-way radio, GSM voice, GSM SMS	Organizing the family on holiday, finding out where the children are
Business person	GSM voice, GSM data, GSM SMS, DECT, trunked radio, GPRS	Contact with clients, remote e-mail, working abroad, viewing webcasts
Elderly person	DECT, GSM, two-way radio	Keeping in touch with helper, ordering food, talking to family

5.2 The User Potential of SDR

Software radio technology will impact mobile telecommunications in a number of different areas, including not only the system itself and applications, but also business models and institutional issues such as regulation, licensing, spectrum, and standards [1]. Three different categories of downloaded software have been defined by the international community in the sphere of radio software [12]:

- high-level applications;
- changes to the middleware, air interface or bearer service; and
- low-level signal processing algorithms affecting the physical layer.

Software defined radio will contribute to a completely connected world with seamless interoperability between systems and services. Potential advantages envisaged for the end user are [13]:

- Enhanced roaming capabilities without changing the terminal. It will always be easy for the user to select the most attractive network (considering costs, quality, offered applications, services) among the available ones in a foreign country.
- Seamless and transparent interoperability between many different communication standards.

- Optimized radio transmission characteristics according to the environment, i.e. to the service and traffic demands.
- Over-the-air download of application software as and when required.

Such a software radio vision is indeed attractive, but a more critical evaluation is required from the user perspective. For example, mobile systems utilizing software radio will need to fit in with evolving user tastes, lifestyles, and technology awareness. Software radio will only be adopted if it truly satisfies real needs of end users, not to mention operators, service providers, and regulators. Key end user trends must be considered, such as:

- *Increased user mobility* due to relocation outside population centers and cheap international travel. Users need mobile devices to enable them to contact mobile friends when there is less chance for face-to-face interaction.
- *Increased demand on the user as employee* to make use of ‘dead time’; to be contactable and to react immediately to work requests whilst mobile.
- *Increased penetration of information and communications technologies*, e.g. Internet, personal computer, personal digital assistant (PDA), mobile phone. Increased user awareness raises expectations and places an increasing demand on wireless infrastructure, terminals, and services.

Insight into current trends and their likely impact on user behavior with evolving mobile systems can be gained from recent market research studies. One such study was sponsored by the Market Aspects Group (MAG) of the UMTS Forum [14]. The report presented a number of key trends that are relevant to next-generation wireless deployment, and possibly beyond. The future views presented in this study provide good motivations for the deployment of software radio technology since this will promote standardization and interoperability, as well as open platforms for service delivery and rich business models. However, there are other less positive views of the mobile future that software radio may support. A report by Ovum [15] suggests that mobile services will suffer strong competition from other means such as wideband broadcast, wired media, and ‘old fashioned’ paper. This report stresses that mobile services must offer an advantage by:

- delivering services which have no substitutes; and
- delivering services more successfully than via other means available.

Advanced data-based mobile services will only achieve higher penetration if they capitalize on their unique properties of convenience, personalization, and total mobility.

The technologist vision of what reconfigurability can offer to the end user, and the market surveys described above, do not in themselves provide insight into how real end user activity with software radio will evolve. There are a number of issues that require investigation, such as, for example, user control of reconfigurability, and the effective and usable presentation of complex system trade-offs. The TRUST project attempted a user-focused approach to software radio technology research in order “to realise the user potential of reconfigurable radio systems”, by understanding users’ requirements from their perspective of the system, and translating these into technology requirements. The user research aimed to provide guidance to the technology research community by investigating scenarios and requirements for end users and operators, to help to identify the frameworks and systems needed to support software reconfigurable radio. A requirements gathering methodology was thus developed to elicit information directly from real end users and network operators in order to anticipate future user needs, rather than relying upon technologists' implicit assumptions of what those requirements might be. The approach taken and some of the early end user requirements that were identified form the substance of this chapter.

5.3 A Methodology for User Requirement Assessment

A traditional user-centered approach (e.g. ISO 13407 [16]) focuses upon the tasks that the user needs to perform. However, to identify user requirements for software radio systems, a 'non-existent' technology intended for use in both business and mass market applications, requires a different approach. These systems are not being developed for one single well-defined user group, carrying out specific tasks, but instead will be used for multiple purposes. As stated above, these factors provide a number of challenges for the investigation of user requirements for software radio. The overall approach adopted is depicted in Figure 5.2. The first phase of this process encompassed the first three stages (Define the User Group; Scope the Technology; Lead Users), and is described in this section of the chapter. The second phase (Develop Core User Scenarios; Iterate with Operators, System Concepts and End Users) is described in the next section.

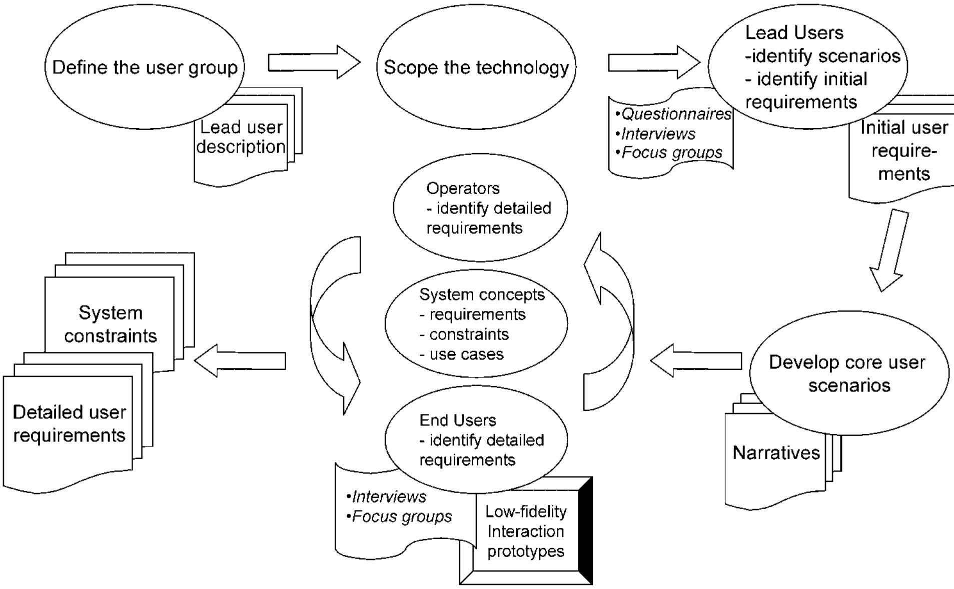

Figure 5.2 User requirements methodology

Given the problems in eliciting user requirements for future technologies outlined above, a pragmatic approach to requirements capture is required. The user interface design literature addresses requirements at three levels, as shown in Table 5.2:

Table 5.2 Levels of end user requirements [2]

Requirement level	Capture method	Example qualitative requirement
High: related to the user's activity, not the system (no mention of user–system dialog)	Observation, interview, focus groups, questionnaires	"I want to control how much a call costs"
Medium: defines what the user is willing to do with the system	Interview, focus groups, subjective and objective tests with paper prototypes, high-fidelity prototyping	"I want to be able to select my network based on cost"
Low: defines the representational and interactive needs of the user interface	Interview, focus groups, tests with detailed UI descriptions	"I prefer iconic representation of service types"

- high (the user's activity)
- medium (what the user is willing to do with the system)
- low (representational and interactive needs of the user interface)

5.3.1 The 'Lead User' Concept

As a means of overcoming the difficulties of describing such a complex and ubiquitous technology as SDR to potential end users, the first stage of the user research was based on the Lead User approach [17]. This approach is a marketing technique used for developing concepts for novel products or services. It is based upon the premise that a small group of advanced users (more advanced even than 'early adopters') already have needs for new products or technologies that will eventually become more widespread, but it will be months or even years before the bulk of the marketplace encounters these needs. Lead Users may meet these needs with today's products or technologies by perhaps using them in different ways to that for which they were originally intended. Thus, by identifying Lead Users, much can be learned about the requirements for these new technologies. A Lead User group of advanced cellular and Internet users, who would have some experience, albeit analogously, with the advantages that SDR is purported to offer, is described in Box 1. (A Lead User description was also produced for the network operator.) Initial end user requirements were then elicited directly from groups of users who met these Lead User descriptions, as is described next.

Box 1: Lead SDR end user description

End user description: *the multimedia consumer at work and at home:* Roams between countries. Relies on the Internet and is used to downloading software to PC or other device. Uses device in buildings, in cars, on public transport, and while walking. Services of interest would be a mixture of audio, text, and multimedia and are mostly asymmetrical. Interested in high-level personalization of the handset and services. Already owns a high-tier GSM phone with WAP capability.

5.3.2 Requirements of Lead Users

From this Lead User definition, a number of user (and operator) interest areas were defined to represent the key technical areas that would affect the end user, and key end user-related questions were identified:

- How willing will users be to be involved in the various levels of terminal reconfiguration?
- How will users control the quality of service offered by a network?
- What levels of certification will be offered?
- What levels of security should be offered?
- How long should a mode switch take?
- What quality/cost relationships exist?
- How big should the terminal be?
- How frequently will software be downloaded?
- What control do users want over multimedia quality in a multimode situation?

These questions acted as a guide for the subsequent requirements analysis.

In order to elucidate relevant requirements from users, example activities and mobile communication tasks using future software radio systems needed to be identified. A key

Table 5.3 Initial SDR situation descriptions presented to Lead Users

Situation (i) [mode switch]
"You have traveled to another country for a client meeting. You have just got off the aeroplane and switched on your phone …"
Situation (ii) [mode switch]
"You return to the UK after your meeting and are walking from a taxi to the train. Whilst still being involved in a call you have the option to move into the coverage of another network …"
Situation (iii) [intramode adaptation scalable multimedia – broadcast]
"You have to watch some live broadcast video whilst you are on the train. As you move the quality of the video is adjusted as other networks and operators are available in this area."
Situation (iv) [scalable multimedia – video call]
"As a result of the video broadcast you need to place a video call to your friend who is supervising work on a building site."
Situation (v) [software authentication and secure download]
"Imagine that the person you had a video call with wants you to run a new application. You want to download this information from the Internet …"
Situation (vi) [personalization through software download – includes bug fixes]
"A few days later you have some free time. You decide to play around with your device. You know that different aspects of the unit can be personalized …"
Situation (vii) [billing]
"It's the end of the month and you need to review your costs. You are using your mobile on a variety of different networks and a variety of services and obviously have to pay for your calls …"
Situation (viii) [battery life]
"You notice that your battery is low. You need to preserve battery life since there is no easy place to charge up."

assumption was that current Lead Users will do with SDR to a large extent what they currently do with their advanced technologies now. Thus, by questioning exemplar users from the Lead User group about their current activities, an indication of critical issues for SDR could be gained. Initial, high-level descriptions of typical situations in which SDR might be used (see Table 5.3) were presented to participants during the in-depth interviews and focus groups, and discussion was held about the current and future technical solutions for each one.

5.3.3 Scenario Development and Use Cases

Based on discussions with these Lead Users, these initial descriptions evolved into a much broader range of scenarios that are described below. A number of data collection techniques (questionnaires, interviews, and focus groups) were used to explore the scenarios with exemplar Lead Users, in order to identify high-level requirements. The resulting scenarios and use cases were wide ranging, although constrained to the likely activities of these ‘Lead Users’. The Lead Users discussed their current usage of those technologies the function of which is analogous to what SDR may offer (i.e. Internet, software download, mobile telephony, GSM network roaming, and device personalization). A view of how current mobile communications and IT would be enhanced by software radio was presented to the users, who then gave feedback with respect to the use of software radio within this future world. In the focus groups and interviews, examples of the varying multimedia quality that could be enabled by air interface and mode reconfigurability were presented, using scalable video sequences. The sequences were used to represent a broadcast call and a multimedia call, and to facilitate the Lead Users’ understanding of the future capabilities of SDR. Three exemplar users were defined: a traveling salesman (Peter), a digital film director (Sarah), and a musician (Alex). These three user profiles (see Table 5.4) were drawn from real people within the Lead User group, and gave rise to a number of scenarios and use cases for software radio.

These exemplar lead users are sufficiently different as to generate a range of scenarios and requirements, and were also selected to avoid focusing solely upon the stereotypical business user. These three exemplar users were used as the basis for scenario analysis. Since it is important that scenarios can map onto system level descriptions, each scenario was subsequently broken down into sub-scenarios (called use cases). Use cases capture particular examples within a scenario and address the most important facets of future SDR, namely: mobility requirements, download behaviors, communication behaviors, environments, and technical areas. The resulting user scenarios and use cases for each of the three exemplar Lead Users are shown in Table 5.5.

Analysis of all data collected from the questionnaires and during the in-depth interviews and focus groups enabled the identification of a number of initial end user requirements for future software radio. A summary of these requirements is provided in Table 5.6. The detailed analysis, breakdown by user type and business/personal requirements, and individual data sources are provided in Ref. [2].

Table 5.4 Lead User exemplars

	Peter	Sarah	Alex
Profession	Sales Director	Film Director	Musician
Work information requirements	Competitor information, e-mail, contacts, schedules, shares, hotels, flights, banking, weather	Contacts, video clips, audio clips, location descriptions	Contacts, MP3 clips, any other audio format clips
Work application requirements	Software updates, virus updates, utilities, demos, video/audio players	Video editing, schedulers, contact list	Contact and schedule management, audio mixing
Personal information requirements	Sports, cinema, holidays, shops, education, houses, cars, shares, banking, pictures	Cinema, holidays, shops, education, banking, pictures	Entertainment, holidays, music technology
Personal application requirements	Demos, video/audio players	Video player, schedulers, contact list	Audio player
Where mobile communications used	Office, home, car, public places, public transport: national and international	Home, indoor/outdoor film locations, car, public transport: national and international	Home, recording studios, car, public transport: national and international

Table 5.5 SDR user scenarios and use cases [2]

Peter: Work Scenarios

Scenario 1. Providing client confidential product information (brochures, text descriptions, video sequences) to clients from wherever I am.

Use Case P1: High-speed access, whilst mobile, to personal storage on corporate Intranet to get product information.

Use Case P2: Access to information near/on client site.

Use Case P3: Have to leave company office to go to client but download started by wire at desk. Need to continue download in car on way to client.

Scenario 2. Link to client at all times (in home building or in car/home/abroad).

Use Case P4: Waiting for an important client call but driving through area of patchy coverage, must receive call.

Use Case P5: Arrive in foreign airport, must make a voice call to client immediately.

Scenario 3. Accessing contacts and schedule when mobile.

Use Case P6: Need access to central contacts and schedule database when in foreign country (with unknown network).

Use Case P7: Need to download new contacts management application.

Scenario 4. Watching streamed Internet presentation.

Use Case P8: Have to leave desktop machine to travel to meeting by train but must keep watching streamed video presentation at highest quality.

Use Case P9: Have to leave desktop machine to walk around building – must keep watching streamed video. Do not mind if quality degrades.

Peter: Personal Scenario

Scenario 5. Organizing family.

Use Case P10: Contact family when car has broken down in the middle of the countryside where there is little/no coverage.

Use Case P11: Send video of where you are to relatives when on holiday.

Sarah: Work Scenarios

Scenario 6. Scheduling appointments.

Use Case S1: Download of new diary application from web site when on train.

Use Case S2: Allow remote clients access to the schedule on Sarah's device.

Scenario 7. Being contactable wherever she is.

Use Case S3: Must receive streamed video clips at home and quickly.

Use Case S4: Move to new country and have immediate e-mail, fax, and video service.

Scenario 8. Traveling to film locations in other countries.

Use Case S5: Need to view footage filmed so far whilst traveling to location. Highest video quality imperative.

Use Case S6: Need to review scripts and storyboards.

Scenario 9. Attending film premieres.

Use Case S7: Meet with collaborators and exchange clips.

Use Case S8: Load clips of latest films in development and send to remote studio.

Scenario 10. Assessing video clips from different filming locations.

Use Case S9: Clips must be received as soon as possible and viewed.

Table 5.5 (*continued*)

Use Case S10: Latest version of editing tool is required. The application is professional and therefore very large.

Sarah: Personal Scenario
Scenario 11. Contacting individual friends from anywhere in the world.
Use Case S11: Need to have a video conference with three friends whilst mobile. Want to see faces on device display. Quality is not important.

Alex: Work Scenarios
Scenario 12. Accessing Internet music when mobile anywhere in the world.
Use Case A1: A pop video has to be downloaded and an audio track must be mixed from Internet samples and added. The final product must be sent to a client. All done whilst on tour bus in another country.
Use Case A2: Working on a new theme tune. Need to download a drum line from a server whilst traveling to studio.

Alex: Personal Scenarios
Scenario 13. Contacting individual friends from anywhere in the world (see Scenario 11)
Use Case A3: Need to set up a multimedia call. Quality is not important.
Use Case A4: Need to send application to friend. Application is large. Quite important that it is received quickly.
Scenario 14. Listening to real-audio radio stations.
Use Case A5: Listen to radio station whilst mobile.
Use Case A6: Record radio for later use in a track. Highest quality is imperative.

Table 5.6 Initial user requirements, derived from Ref. [2]

High Level Requirements: User Needs

- Need to work effectively when mobile
- Like to show off the things I own (status)
- Like to reconfigure and personalize devices, e.g. PC, Palm
- Like to have control over devices and add what I want
- Operators can only differentiate on customer support
- SDR must offer more than the Internet
- May only use the phone for short-term needs
- Want freedom (to move between networks) and flexibility (to choose services)
- Need communications when traveling
- Technology must work at all times
- Always need to be contactable
- Need to talk to groups
- Want to be able to use mobile device for everything, as with the Internet
- Want to change devices but keep data
- Will choose a network with a good brand image

	● Want a device that is ‘confidently multifunctional’ ● Do not want to be bombarded with information from all the different networks being used ● Do not trust big corporations to send me anything ● Do not have time to be playing with phone ● May be cynical about new technologies as ‘all marketing’

Medium Level Requirements: System Needs

Download	● Download needs to be secure ● Should be protected against viruses ● Device should not download anything without user’s permission ● Want some control over what information and applications are downloaded ● Device must be fully operational whilst downloading ● If special software is required to view downloaded information, this should be downloaded as well ● Fixes for bugs should only be downloaded if user has found the bug ● Want to download anything used at work or on PC ● New software must inter-operate and be compatible with software already on the device ● Installation of new software must be very quick (no slower than Palm or PC) ● Download should be as easy as the Palm ● Would want to download and use software on long journeys in car, train, plane ● Would like to share software between colleagues ● Download of data may be more likely than applications
Air interface	● Often want to just switch on and make a call, and then won’t care about the network ● There must at least be a good signal everywhere and access to the network for all calls ● Must be able to roam in home country ● Want to be able to go to another country and just switch the phone on and use it ● When abroad there should be no need to dial an international code to another person who is roaming in the same country ● Set cost constraints as a preference for networks (bearers) ● Want to see cost and service parameters (coverage, functions) of available networks before making a change to a new network ● Want some generic measure of network quality (e.g. coverage or capacity restrictions) to help select networks ● Changes between networks (including LAN to WAN) should be seamless ● Want to change network settings regularly to satisfy current value constraints ● Don’t mind automatic roaming, but the device should be more intelligent and roam on more parameters than signal strength, e.g. cost ● Don’t expect to pay for intra-standard changes (e.g. one GSM network to another)

Table 5.6 (*continued*)

	● Willing to let the device search for the best network in terms of cost and data capacity, user constraints or available incentives
	● Could be like an auction where user says they want a service at a certain cost and network operators bid for their business
	● User expects to gain something by playing around with network settings
Battery	● Need more detailed information to help make call charging/call decisions
	● Want very efficient use of the battery for video
User interface, services, application download	● Want access to a familiar virtual desktop from wherever user is
	● User interface needs to be easy to use, setting parameters must be quick
	● Cost constraints need to be set as a preference for services
	● Happy to let the device shop around for the best services
	● Would like the network to send location-specific information e.g. traffic information in the car
	● Don't want to receive lots of 'spam' advertising
	● Want more than glorified SMS
	● Must be a human customer support mechanism since the device will be so complicated
	● Want somewhere where user can take device to get help, like a car service center
	● Want preferences for e-mail and fax for use abroad
	● Business calls need a solid reliable line
	● Advertising of services needs to be simple since users make quick decisions to purchase
	● Interested in downloading games to pass the time
	● Personal software should be free because it's just for fun
	● Want a quick messaging service to contact friends; should be able to use this anywhere
	● Third party should handle the complicated billing: a provider of network providers
Multimedia	● Would alter video quality in real time
	● If user knew there was better quality available, they would want it
	● For business video calls the user needs to see subtleties; especially in business, you need to tell when people are lying
	● Willing to pay more to make call (business)
	● Should be a way to trade quality against services
	● User doesn't want to play with video quality parameters
	● Not concerned about poor quality when talking to family/friends
	● Would rather download video and watch later
	● Would like to 'e-mail' voice and pictures
Low Level Requirements: Specific Device Needs	
Download	● Have different work profiles which can be changed
	● Icons for different applications
	● Download applications like applets on the web

Air interface	● Warning (e.g. beep) before network transition
	● Indication of network range so user is aware of imminent changeover
Battery	● Indication of how much time left on the battery
	● How much time available for a particular type of call or download
User interface and services	● Terminal display should be high resolution
	● Want to set up preferences for different parts of the world, e.g. fax numbers, e-mail
	● Want to access language translation services when abroad
	● On business trip in new city, users want to be presented with information and applications relevant to that place
	● Physical size of device should not be restrictive for entering text
	● Device should look/sound different on the outside; different ring tones
	● Need information when traveling: translations, maps, yellow pages
	● Want to change look of phone and computer with different covers and desktop designs
	● Would like to receive information based on user's interests
	● Want PDA and phone together
	● Like to change handset regularly to be fashionable
	● Want a button to press to say 'I'm here'; position information sent to who user is calling
Multimedia	● Want to see what parameters of the video can be changed in real time
	● Want to see what quality of video will be before paying
	● Want a way of integrating a digital camera so pictures can be sent

5.3.4 User Categories

Clear user characteristics relating to possible use of a SDR device emerged during this data collection exercise and two distinct user categories ('Gadget Crazy' and 'Don't Touch It') could be defined. These characteristics cut across work and business situations, as well as across gender.

'Gadget Crazy':

- interested in technology for its own sake;
- willing to reconfigure devices to match personal needs; particularly network and service selection;
- sees the SDR world as a challenge and a way to demonstrate technology awareness;
- embraces new technologies;
- wants to know why the system has done a certain thing.

'Don't Touch It':

- sees technology as an enabling tool and is therefore interested in using it effectively;
- would like the device to take care of most decisions about services but wants overall control;

- interested in aesthetics of devices and the fashion statement it makes about their individuality;
- cynical about new technologies, e.g. WAP, assumes built-in obsolescence.

These two user categories demonstrate the importance of understanding the different requirements that users bring to technology, even when a Lead User description is defined. It also demonstrates that technologists should not aspire to developing a ‘one size fits all’ solution, since clearly the resulting device will not meet the needs of all users.

5.4 From User Scenarios to Detailed Requirements

In the first phase of user requirements research described above, over 20 reconfiguration use cases were defined (Table 5.5). The second phase of research involved the selection of those use cases which were to be taken forward for detailed analysis, both in technical research and in further requirements analysis in the form of low-fidelity prototyping and user evaluation. The way in which the four core user scenarios were developed is described below. However, we first consider the value of a scenario-based approach in user-centered research for future technologies such as software radio.

Scenario-based design provides a means of taking into account the future use of the interactive system that is being designed. Scenarios are simply stories that describe people using an interactive system. As such, scenarios highlight what the user wants to do with the system [9]. A scenario typically consists of a *setting* with an *actor* who has a *goal* or *objective*, and includes sequences of *actions* or *events*. By representing the use of a new system with a set of interaction scenarios, the future use of that system is made explicit. This can help designers to focus attention on their assumptions about the user, and the way in which users will interact with the future system. Equally, scenarios can be used to present novel concepts to end users in order that their interaction needs are considered within the design process, and as a means of developing end user requirements for non-existent technology. Other stakeholders who are likely to be affected by the introduction of a new system or technology can also examine the same scenarios to consider their own requirements for the new system. Thus, a scenario-based approach can provide a number of benefits as users, stakeholders, and system developers are all provided with a suitable context in which to explore and communicate the system’s requirements and constraints.

The next phase of research focused upon developing detailed narratives and storyboards for four core user scenarios, briefly described in Table 5.7. These scenarios were selected and developed to explore specific areas of interest relating to end user and operator requirements and system aspects. They may be used to elicit detailed end user requirements through the use of interactive storyboards, and also to consider operator requirements through discussions with other stakeholders. These high-level scenarios also drove more detailed UML modeling activities which were used to represent the functionality and interactions of system modules within the overall system architecture [18]. Trade-offs between the initial user requirements and system constraints could be investigated around these scenarios, and more detailed requirements generated.

A storyboard was created for each of the scenarios, breaking down the user interaction into discrete items, which enabled us to consider, at each stage of the scenario, the implications for the end user, the network operator, and ultimately the relevant system module state. The

Table 5.7 Core user scenarios

Core scenario	Original use cases (Table 5.5)	Description
1	P3	'Providing client confidential product information (multimedia) to clients wherever I am.' Must leave office to go to client site but download from secure corporate Intranet started by wire at desk. Need to continue download in car on way to client. Device detects best networks for this transaction.
2	P4 (P5, P10, S4)	'Being contactable wherever I am.' Waiting for an important client call but driving through area of patchy coverage. Must receive the call, even if device is in use. Device reconfigures to maintain coverage. Important call is detected, and current call is paused.
3	S5	'View high quality video.' Need to view high quality video whilst mobile at speed in a foreign country. Need to download specialist codec to be able to view video format. Device has insufficient memory for new software, and so user needs to delete air interfaces not currently required.
4	S11	'Mobile video conference.' User wants to be able to contact individual friends from anywhere worldwide. Needs to have a video conference with three friends whilst mobile, want to see faces but quality not important. Participants all in different locations.

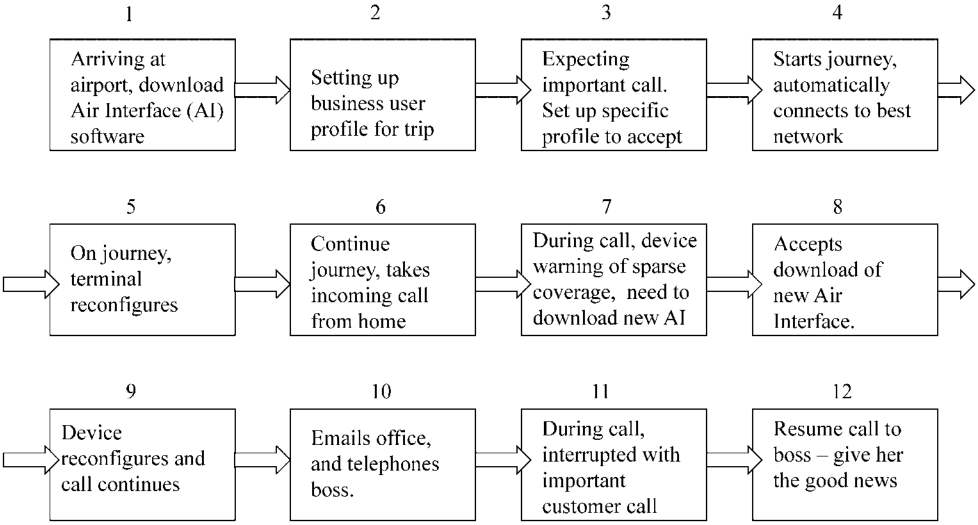

Figure 5.3 Storyboard for user Scenario 2

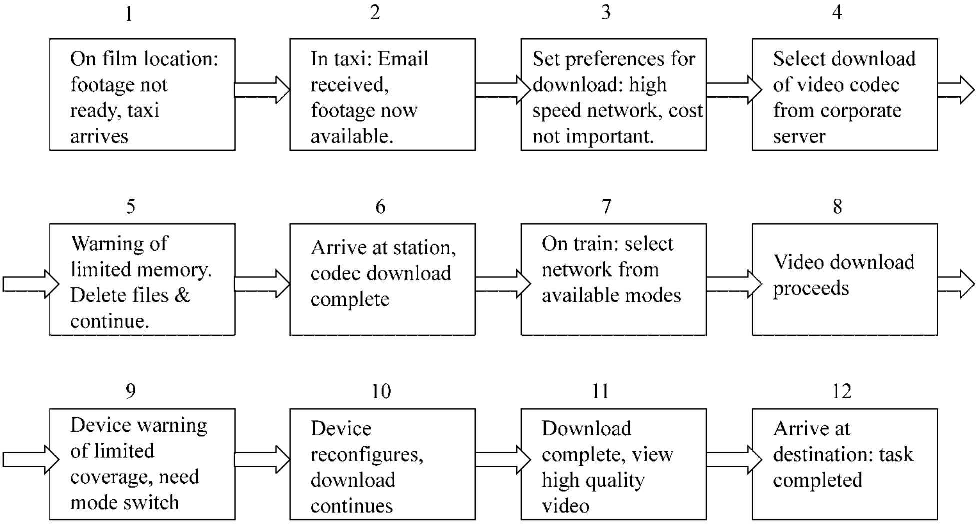

Figure 5.4 Storyboard for user Scenario 3

Table 5.8 Example user interaction issues for user Scenario 2

Stage	User interaction
1	Suitable mechanism for user to download air interface software immediately on arrival in a foreign country. User interface to provide user with feedback on available services, costs, coverage.
2	User interface or profile ‘wizard’ to enable user to set up a profile to always accept reconfiguration to give best coverage, but to be informed of cost and services available. Investigate how often users would be willing to set up new profiles.
3	Interaction dialog to enable user to set up a specific profile to accept one particular call, and to be interrupted to receive it.
4	User interface to enable user to view characteristics of mode selected automatically by the device (to meet his profile).
5	Feedback to the user that the device is reconfiguring (automatically as set up in profile), and of cost and functionality now available.
6	User interaction to take incoming call.
7	Provide a warning during the call that there is sparse coverage available.
8	Feedback to user on cost of download, available functionality, and any impact of download on battery life.
9	Feedback to user that software downloaded and device is reconfiguring. Feedback on functionality available.
10	User interface to enable the user to make a phone call at the same time that he is writing the e-mail.
11	Feedback to the user that the specified incoming call is detected. Feedback to the user that current call and e-mail are being interrupted to receive the call.
12	User interaction to resume original call and e-mail.

Table 5.9 Example user interaction issues for user Scenario 3

Scenario stage	Description
1	
2	User interaction for receiving and reading e-mail.
3	Suitable interaction dialog/'wizard' to enable user to set up a specific preferences profile, to download high-quality video. Investigate with users 'ease of use' of 'wizard'.
4	Suitable interaction dialog to request download of video codec. Suitable feedback on cost of download.
5	Suitable feedback on insufficient resources available. Suitable interface to enable user to search software modes and size of files. Interaction to delete unnecessary software modes. Interaction to resume download.
6	Feedback when download complete and codec installed.
7	Suitable user interface to enable user to view available network modes that meet preferences; view cost and bit rate information in easily understandable format. Investigate what information users need, and how this should be displayed. Investigate with users how to represent trade-offs in cost and network speed for downloading scalable video. Suitable user interaction to select preferred mode and connect.
8	Suitable feedback to user of download progress.
9	Provide a warning during the video download that there is sparse coverage available in this mode. Feedback to user the need for a mode switch to continue download. Investigate if users would want to be warned of imminent reconfiguration, and how seamless this should be, or what information they would want to know. Suitable feedback to user on available functionality, cost, and bit rate. Investigate with users what an acceptable delay for reconfiguration would be.
10	Suitable feedback to the user that the device is reconfiguring, and cost, speed, and functionality now available in new mode. Suitable user interaction to resume download (if necessary).
11	User feedback when download of video file is complete.
12	

Box 2: Detailed description of user Scenario 2

Peter is away from home on business in the US. On arrival at the airport he needs to be able to download appropriate air interface software to enable him to use his TRUST device on his trip. He wants to be able to use his device to send and receive e-mails, faxes, and multimedia calls. He has to pick up a hire car and drive to visit a client who has her office in a sparsely populated area of South Carolina, where there is less network coverage available. Before setting off on his journey, Peter sets his user profile to search for and accept complete coverage at all times, regardless of costs. Driving in a foreign country in a remote area, he also wanted to make sure that he could make calls at all times, and so he sets up these user preferences in his profile. He does this so that his TRUST terminal will automatically reconfigure to the best available network to ensure he is always contactable and can make calls as a minimum service, and he can then make use of the best network coverage available to meet those needs. Today he is expecting a very important call from a French client who is close to deciding to place a very large contract with Peter's company. This contract will bring Peter's company a lot of business, and earn him a hefty bonus. In the interest of maintaining a good customer relationship it is vital that Peter receives this call, even if at the time he is already engaged in another call or otherwise using his TRUST device. He sets up a request in his user profile for the terminal to interrupt him with this one particular call, and then sets off on his journey. As Peter drives further away from densely populated areas he notices from the TRUST display that his mobile device is reconfiguring from the first network to a second one. This is carried out automatically (following his user preferences), but he still receives notification, as the second network is more expensive and there are fewer services available. Driving on, Peter receives a voice call from his wife. During this call, his device alerts him that if he wishes to accept complete coverage he will need to download an air interface for a new network. Peter is provided with details of how much this will cost, and what functionality will then be available to him. Peter pulls over, and he chooses to download and reconfigure to the new mode as he wants to maintain his availability to receive his important customer call. Peter suddenly remembers that he was supposed to e-mail some financial information to his boss, and so he starts writing the e-mail. He also needs to call his boss to clarify an item. During this voice call, the TRUST device alerts him that his important client is trying to call and the device automatically pauses the voice call between Peter and his boss and connects the call from his client. It was good news, which Peter was able to pass on to his boss when he resumed that call immediately afterwards.

Box 3: Detailed description of user Scenario 3

Sarah is away from home on film location in North Africa. She has to leave this location to check on progress with preparations for filming at a different location. Unfortunately she hasn't had an opportunity to view the footage that has been filmed over the last couple of days, but hopefully she can download this on to her mobile TRUST terminal while she is traveling to the new location, and will have time to view it before she arrives. They are in a fairly remote spot, and she will have to travel by taxi to the nearest train station, approximately 30 minutes away. The taxi arrives and she sets off. During this journey, she receives an e-mail on her TRUST terminal from her colleague, telling her that the footage is ready, and reminding her that she will need to download the specialist video codec to view this professional video format, as well as the footage itself. Sarah sets her terminal preferences to enable her to download the codec and video file: fortunately, because the TRUST device is well designed and easy to use, she is easily able to do this. She is not concerned with cost, as this is a business transaction and it is vital that she sees the footage as soon as possible. During the download, her terminal alerts her that the device does not have sufficient memory. Sarah has the choice of either canceling the download, or pausing and deleting some files on her device that she doesn't need for this trip. Sarah searches all of the different software modes that she has downloaded for different trips, and realizes that she won't be needing air interface software for the US West Coast for a while, or for Japan. She deletes these two modes, which means that she has more than enough memory free for both the codec and video file that she will need. The download of the codec resumes. Meanwhile, the taxi has arrived at the station and Sarah boards the train for her two-hour journey to the new location. Once on the train, Sarah reconnects to the best available network to enable her to download the film footage. It is very important that the footage is of high quality to enable Sarah to do her job, and so she selects the highest quality of scalable video that is available. This means that downloading the file is more expensive as Sarah will need to download the maximum number of video layers and it will take longer, but she has no choice but to pay for this. Whilst downloading the video file, the TRUST terminal suddenly warns her that there is now limited network coverage in her current mode, and that she will need to accept a mode switch if she wants to continue the download. Sarah checks the services and cost of the new network that is available, and sees from the display that as there is a lower bit rate, downloading the high-quality layers that she needs will now take a bit longer, and will cost more. She accepts the extra cost, and the device reconfigures to the new network. The download is eventually complete, and Sarah is then able to view the video footage on her TRUST device. She is impressed with the high quality of the video, and is able to complete her task before she arrives at her destination.

detailed scenario descriptions for Scenarios 2 and 3 are shown in Box 2 and Box 3, respectively; the storyboards are shown in Figures. 5.3 and 5.4, and examples of the detailed end user issues that were identified for each are shown in Tables 5.8 and 5.9.

There are a number of SDR research issues that are being addressed in these scenarios. The main issue under investigation within Scenario 2 is the challenge for software radio technology to support an immediate and constant capability for the user to send and receive calls. In this scenario, the user arrives in a foreign country without the necessary air interface software already installed on his device, and then travels through areas of patchy coverage but wants to be contactable at all times. There are many issues to be explored with end users in this scenario in order that detailed requirements can be gained. For example, it will be necessary to gain sufficient understanding of the extent to which users will be willing to set up and change their user profiles to meet their changing needs. It will also be necessary to develop a suitable means of providing the user with sufficient and clear feedback on the implications of accepting a mode change (e.g. cost and available functionality).

Scenario 3 explores a situation in which the user needs to carry out a task using multimedia, whilst mobile. In this scenario, the user needs to download a professional video codec to enable her to view some film footage. The scenario is very demanding from a technology perspective since the user is traveling at high speed in a foreign country. Software defined radio issues to be explored include the challenge of maintaining the reliability of a physical link for the download of a large video file whilst mobile, and considering the possible impact on the device's functionality and power management during such a large download. Business issues to be considered include the accessibility of professional software for download over the air, and devising a means for network operators to charge the user for such a service. Issues to be explored with end users include the provision of suitable feedback on the availability of resources and device functionality, and investigating how the trade-off between cost, network speed, and potential limitations on the device's functionality could be represented. In all scenarios, the issue of providing an intuitive user interface with suitable feedback to the user of an imminent device reconfiguration, will need to be investigated. It is imperative that future mobile systems incorporating software radio technology enable the user to make informed decisions about accepting or rejecting a new mode, whilst fully understanding the associated cost implications.

5.5 Benefits and Limitations of the Methodology

The scenario-based approach described in this chapter has provided a means of exploring real end user and operator requirements for SDR, providing an alternative to the approach of relying upon technologists' own assumptions of what technology can offer. These scenarios have provided context to enable meaningful discussions and investigations not only with end users and operators, but also between researchers working on different aspects of SDR.

The output from this approach is not a long checklist of testable requirements, but rather a selection of meaningful questions and apparent requirements that can be explored and refined in an iterative fashion, as the technology develops. Thus, at the early stages of research into software radio, these scenarios have been used to clarify assumptions of how this complex technology may be realized. For example, it was initially assumed in Scenario 1 that the user would need to pause a wired download when the device is physically removed from the wired connection. However, detailed discussions around this scenario resulted in agreement that the device itself could automatically detect when a wired connection became unavailable and automatically revert to a previous wireless mode, which need not impact upon delivery of the current service (in this case a file download).

Perhaps one limitation of the scenario approach is that the coverage of a technology's use will inevitably be incomplete. To some extent such a criticism of scenario-based design will always be true, however, steps can be taken to mitigate this. In the case of the software radio research this was done, for example, by reviewing and adding to the scenarios after their first iteration to include additional use cases (e.g. insufficient memory being available on the device, and the need to revert to a previous mode for power management).

The next steps for this research will be to investigate in more detail the end user and network operator issues that were identified in the four core scenarios. Interactive storyboards depicting each of the user scenarios have been developed (using Macromedia Director) as a means of portraying the capabilities of SDR to end users in structured interviews and focus groups. In this way, increasingly detailed end user requirements will emerge, covering aspects such as user interaction, information representation, user profiles, and overall acceptability of SDR.

5.6 Conclusions and Future Directions

A user-centered approach can add significant value to the research, design, and development of future generations of mobile communication systems enabled by technologies such as software radio. User needs must be identified and understood if the full potential of such technologies is to be realized – successful products will be those that are useful (they apply the technology to enable users to achieve their goals) and are usable (easy to use). There are many user-related questions relating to software radio yet to be answered; this chapter has sought to present one approach to developing an understanding of the user's perspective of software radio.

The first phase of this approach focused upon eliciting initial requirements for software radio from Lead Users of analogous mobile devices. This approach was adopted in order that some of the difficulties in describing a complex and ubiquitous technology such as software radio to users could be overcome. A summary of these initial requirements was provided in this chapter; a complete description of the process and resulting requirements analysis can be found in Ref. [2], which also reviewed a number of secondary data sources. The following conclusions were drawn from these studies:

- SDR-supported mobile devices and services will only be attractive to users if they fulfill a need which cannot be satisfied by other means;
- SDR will succeed as an enabling technology if it supports the key wireless advantages of global portability and user intimacy;
- services supported by SDR must be designed in such a way that the key barriers to mobile uptake are addressed, namely: absolute simplicity, reliability, affordability, personal relevance;
- quality of service needs will be task- rather than application-dependent;
- the user sees the terminal and network as one interface; deficiencies in one will impact the perception of the other;
- care must be taken in the design of products and services such that they integrate with social activities in the home environment;
- requirements for SDR are highly contextualized by the technology and the usage environments; this makes the requirements capture process difficult.

The initial requirements were drawn from the Lead User group; even within this group, however, the results showed a diversity of needs and attitudes. These initial requirements can be summarized into two broad categories of business and personal requirements for software radio.

Business requirements:

- cost is not important
- high-quality images (frame rate and resolution, high data rate) will be important
- will need coverage and immediate access to services
- business services required will include local information and translation
- productivity applications and time-fillers (e.g. games) are likely candidates for software download

Personal requirements:

- best cost and quality (voice, image, bit rate) combination is important
- user has time to play around with the device, particularly for personalization

- user is willing to compromise quality for cost
- service purchasing decisions are ad hoc
- user is conscious of network provider brand image
- simple messaging services and location-aware services are important

The Lead User approach was extremely useful in the first phase of this user-centered research as it provided a recruitment template for participants for the questionnaire, interview, and focus group studies. It was considered that only this type of user would be likely to understand the flexibility of use that software radio will enable, by considering and describing their current activities with analogous devices. However, after this initial phase of research and the identification of initial requirements, the focus of study was expanded beyond this narrowly defined user group. One of the risks of investigating only Lead Users is that the results and conclusions are based upon only a small section of the population, whereas software radio will become a ubiquitous technology ultimately used across the whole spectrum of users with varying skills and comfort with technology. It is therefore important to consider a wider range of users in the next phase of this research.

The second phase of the research thus focused upon developing a small number of core user scenarios that were explored in greater detail. The main advantage of using scenarios is that context can be provided to the end user, which enhances their understanding of the concepts involved. We have found that the scenarios have proved to be useful not just for exploring user requirements with end users, but also for considering the implications of software radio for the network operator (see Chapter 6). The scenarios have also enabled researchers to discuss assumptions that were being made, and to clarify a number of technical issues with regard to the overall system architecture.

To some extent, more questions have been generated than answers. It is hoped that some of these questions will be answered in the final phase of user research within TRUST, and that other research will answer yet more of these. The research described herein has been a useful first step in demonstrating how a user-centered approach can provide a focus for the research and development of future technologies such as software radio. The full benefits of such an approach will only become evident much later on.

One of the challenges for user-centered research in this field is the fact that mobile communications technologies are evolving rapidly. We are asking end users and network operators to consider future products enabled by SDR when their understanding of emerging 3G technologies is not yet mature or in many cases even existent – users' perspective of SDR is likely to evolve as and when they gain more experience with these new 3G systems. Users' expectations are shaped by their current experience with today's technologies, and so our requirements will need to be revisited once these technologies become more mature and are in widespread use. In practice, many of the user issues that have been identified through the research to date may prove equally relevant to the 3G systems now being deployed, and are likely to be of value to 3G developers even in the shorter term.

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6

Software Radio: The Mobile Network Operator Dimension

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Today's rapidly changing business environment is creating intense competition among corporations. Markets are changing faster now than in any other time in their history. Product life cycles are shortening and businesses must compete globally. This competition is especially fierce in the wireless communications market, where operators are struggling without rest to increase their market shares and revenues.

In the beginning, the match for leading the cellular market was played in the tariffs arena. However, today this match is nearly over and operators must look for new battlefields in which they can defeat their competitors and increase revenues. And the most promising battlefield is undoubtedly the provision of new high value added services.

The SDR Forum defines software radio technology as "an emerging technology, thought to build flexible, multiservice, multiband and reprogrammable by software, radio systems". Actually, software radio is seen as the technology that will allow users to gain the ubiquitous access to information. This means they will have the capability with a single mobile terminal to access any communication network, anytime and anywhere in the world. Due to this fact, operators will have access to a global world market, offering services to their customers inside and outside their own home networks.

Moreover, the flexibility and reconfigurability of software defined radio (SDR) systems will allow operators to design and provide many new value added services, totally customizable by the end user. These services will be completely adapted to end user requirements following the customer-oriented market strategies predominant in business nowadays. Operators offering these new customized services will definitely defeat their competitors in the market share battle mentioned above.

This chapter aims to show the enormous potential of software radio technology for cellular network operators and service providers. Firstly, an overview of the evolution of the mobile

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[1] The ideas contained in this chapter represent the views of the authors and do not necessarily reflect the official position of Telefónica.

market during the last few years is provided, in order to describe the trends that have made SDR technology something desired by all the players involved in the cellular radio business.

The deployment and subsequent commercial exploitation of third-generation (3G) wireless communication systems will alter significantly the value chain that has traditionally prevailed in second-generation (2G) markets. New players will enter the chain and consequently new relationships will be created. Of course, SDR technology will cause a new revolution, modifying again the former value chain. In this chapter, both 3G and SDR value chains are described, emphasizing those changes that can especially affect operators' current position and activities.

In cellular radio, SDR technology has two main potential users: end users and operators/service providers. Both of them will establish a set of requirements that SDR will have to satisfy in order to succeed in the markets. An important part of this chapter deals with operator and service provider requirements.[2] First, general requirements are elicited, showing the potential impact of SDR in allowing the emergence of reconfigurable networks. Afterwards, three use cases, related to the three software download levels proposed by the SDR Forum, are described. Each use case description includes specific SDR requirements.

Finally, in order to illustrate the three general use cases mentioned above, some particular use cases and business models are proposed. These models will provide readers with a key idea that they should keep in mind when thinking about software radio: the economic potential of this technology is enormous and will significantly alter the current situation of the wireless market.

6.1 Evolution of the Mobile Market: An Operator's Perspective

The adoption of the software radio concept will ultimately depend on it being economically attractive for service providers, operators, manufacturers, and users. In this section, a brief analysis of the current situation of the mobile market and its foreseen evolution is presented, in order to demonstrate the economic viability of SDR technology.

The mobile communications market has undergone a spectacular growth worldwide during recent years. Currently there are more than 725 million mobile subscribers, an increase of 54.2% in year 2000 alone. This growth has been especially significant in Europe where the number of mobile subscribers has increased by 57.5% passing from 153 million at the end of 1999 to 241 million at the end of 2000. This trend is expected to continue in the future, reaching 400 million in 2005 according to Ovum estimates [1]. Figure 6.1 shows the recent and projected evolution of the number of mobile subscribers in several European countries. It is important to notice that up to 36% of this growth comes from just five countries: Germany, France, United Kingdom, Spain, and Italy.

In the US the mobile market has also grown but at a lower rate, passing from 86 million subscribers in December 1999 to 118 million in December 2000, resulting in a 37.2% increase (sources: Ovum and CTIA). Clearly, the European market is evolving faster than the American market.

The anticipated wireless market growth in Central Asia is very high, where the number of subscribers is expected to rise from 94 million at the beginning of 2001 to 355 million at the beginning of 2005.

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[2] End-user requirements of software radio have been described in Chapter 5.

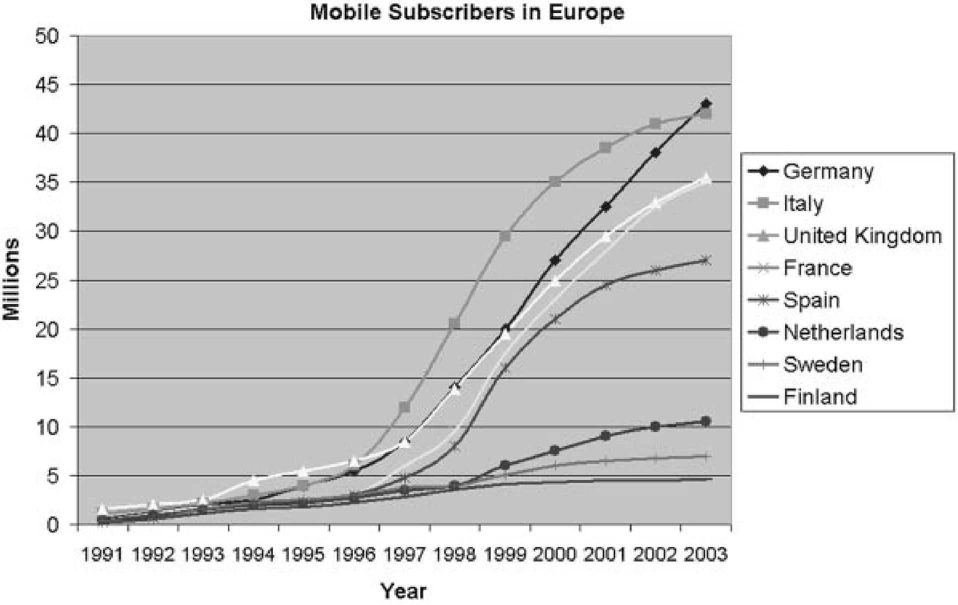

Figure 6.1 Evolution of the number of wireless subscribers in Europe

High growth rates are also expected in other areas. Asia-Pacific falls into fourth place with over 139 million subscribers at the beginning of 2001 and 254 million connections at the beginning of 2005. In South and Central America, the number of wireless connections will increase from 70 million at the beginning of 2001 to 234 million at the beginning of 2005. Likewise, in the Middle East and Africa wireless subscribers will rise from 37 million at the beginning of 2001 to more than 156 million at the beginning of 2005.

The number of Internet users is also increasing rapidly all around the world. In this case, Europe is running behind the US and, although the distance is shortening, an important gap still exists. According to a report by International Data Corp. (IDC) [2], the number of total Internet users worldwide will reach 602 million in 2003, with the proportion of American users dropping from one-half in 1998 to one-third in 2003. The fastest Internet user growth is in the Asia-Pacific region, where it will triple to 75.6 million from 19.7 million between 1999 and 2003. If the current trend continues, Europe will catch up with the US in year 2003, having also one-third of total Internet users. In e-commerce the gap between the American and the European areas is also reducing very fast with European companies taking the lead due to their global strategies.

Again according to IDC estimations, the so-called Dot-Com Crash will not mean the end of e-business. On the contrary, companies around the world will invest more money on their web site infrastructure this year alone than they did in 5 years preparing for year 2000. Though Internet stocks have rapidly fallen in the markets, Internet technology is increasingly being adopted as a fundamental and essential part of traditional businesses. In fact, over the next 4 years, the number of web sites will double, e-commerce will increase by a factor of 10, and technology spending on web applications will grow up to four times what it was the previous 4 years.

Observing the revenues distribution among three different agents involved in the Internet access market, internet service providers (ISPs), online service providers (OSPs, i.e. ISP + portal), and portals, it is obvious that the real business resides in the portals side (see Figure 6.2). This is due to the fact that the portals receive approximately 75% of Internet publicity revenues (the largest piece of the Internet revenue cake). This reality has not been neglected by network operators that have already launched their own mobile portals, offering access to an increasing variety of services.

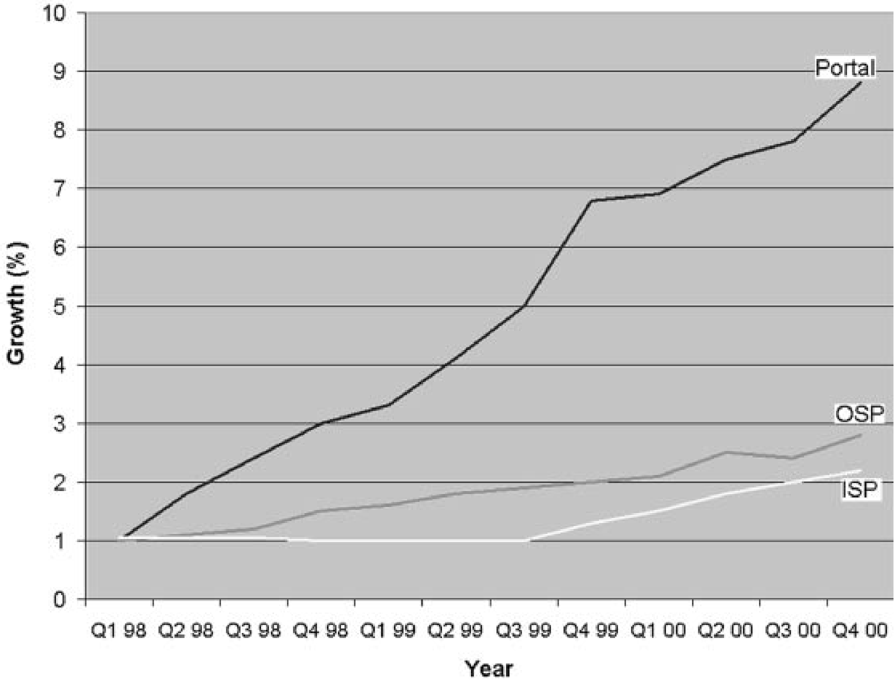

Figure 6.2 Evolution of revenues for portals, OSPs, and ISPs

But the most interesting fact is that these two markets, mobile communications and Internet, are converging and it is in this new paradigm where reconfigurable radio systems can play a definite role. Until now, mobile operators have received nearly all their revenues from voice services. The incorporation of Internet-based services will change this situation, conferring increasing importance to data services. In Figures. 6.3 and 6.4 (elaborated according to Mobile Data Association forecasts), the expected evolution of Western European and US cellular data revenues has been represented. An important part of this traffic will consist of applications downloaded from a remote server using any available downloading protocol such as, for example, the different mobile execution environment (MExE) classmarks. If reconfigurable radio finally succeeds, mobile data traffic is likely to increase considerably because not only applications but also protocols and algorithms will be downloadable from remote network servers to the user's terminal.

Economic viability of reconfigurable radio systems can be inferred from an analysis of the economic success of existing download protocols. The first commercial system of this kind

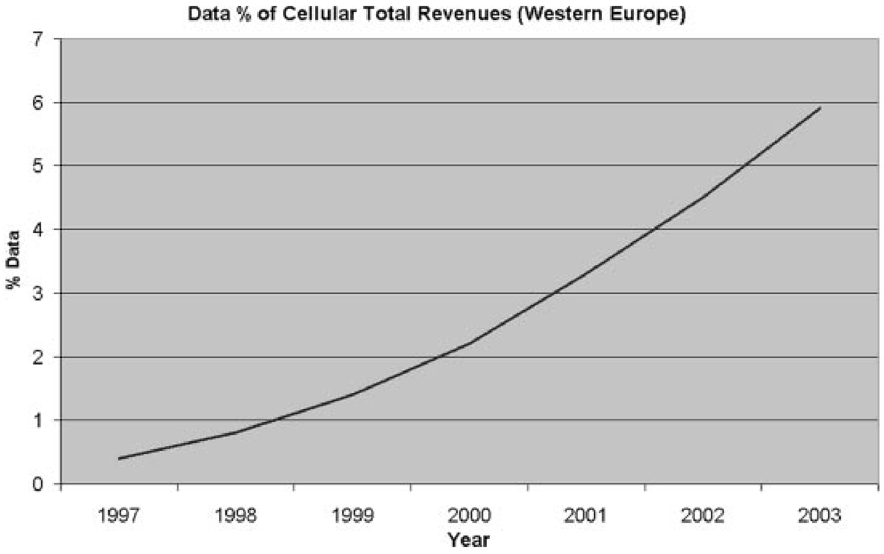

Figure 6.3 Proportion of total cellular revenue coming from data services in Western Europe

was the *i-mode* system, launched in Japan in February 1999. This system saw incredibly rapid success and just 9 months after its launch there were more than 2 million people (or 8% of the mobile subscriber base) using the service. By March 2001, the number of subscribers had already reached 21 million. *i-mode* is not based on circuit-switched technology, like currently available wireless application protocol (WAP)/global system for mobile communications

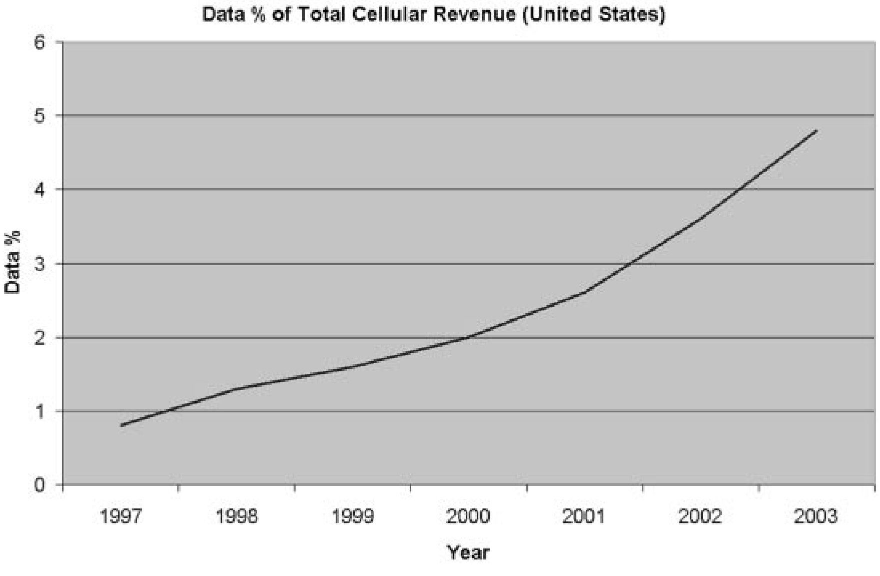

Figure 6.4 Proportion of total cellular revenue coming from data services in the US

(GSM) technology, but rather uses a Japanese packet mobile data network (with a protocol similar to general packet radio services (GPRS) on GSM networks), which requires special *i-mode* handsets. More than 1000 content providers have developed official sites for the handsets, mainly financial services (banks, brokers, credit cards issuers) and insurance companies but also ticket and travel agencies as well as newspapers, CD and book sellers, and games and entertainment services. Moreover, the number of unofficial *i-mode* sites is nearing 20,000, widening even more the content catalog.

In Europe, WAP is the choice of network operators for downloading applications to their subscribers' handsets. Whilst early user experience of WAP has failed to live up to users' expectations, many expect the advent of GPRS to change this. Most network operators already have Internet and WAP portals that provide users with access to many different services. For example, BT Cellnet launched its Genie portal very early and obtained a near immediate success gaining more than 200,000 subscribers. Most of these portals run by operators have restricted the access to their own subscribers. BT Cellnet decided to give up this approach in order to gain critical mass and opened up Genie in 1999 to customers of other networks as well. Many independent portal operators in Europe are also offering customized services to mobile users using WAP and short message service (SMS).

In 2005 there will be around 730 million subscribers accessing information from the Internet using a mobile device, according to eTForecasts estimations [3]. This will represent 62% of total Internet users and nearly 50% of mobile phone owners worldwide. Europe will continue leading the US, with 168 million wireless Internet users (68% of total European Internet users) and 83 million (39% of total American Internet users), respectively.

If these limited download techniques are already having such a success in the markets, it is possible to imagine the enormous economic potential of defining a download protocol which allows to reconfigure not just the application layer but the whole communications protocol stack of the radio system. A small part of this potential will be unveiled when some use cases are described in the last sections of this chapter.

6.2 3G and Beyond, a New Value Chain

The deployment of 3G mobile networks will modify the current wireless market value chain in a significant way. The new service capabilities supported by 3G systems will allow a set of new players to enter the wireless communications arena; current operators feel seriously menaced by these new players who could take part of their immense revenue cake. To understand the roles played by these new agents it is useful to analyze how they will fit in the wireless value chain.

Third-generation mobile systems will deeply modify the current wireless value chain structure. These changes stem partly from the fact that 3G will allow operators to provide broadband multimedia data services, which in the past was just a far off utopian vision. These services will consist of applications and contents that can come from many different sources such as application developers, content creators, content aggregators, etc. In Figure 6.5 the 3G value chain has been represented, showing two different levels of detail.

The first level of detail just considers the three main parts of the cellular radio business:

- Services: Designed to attract subscribers and generate revenues. Third-generation systems will introduce a multitude of new value added services and many of them will probably affect our current way of life (hopefully increasing our quality of life).

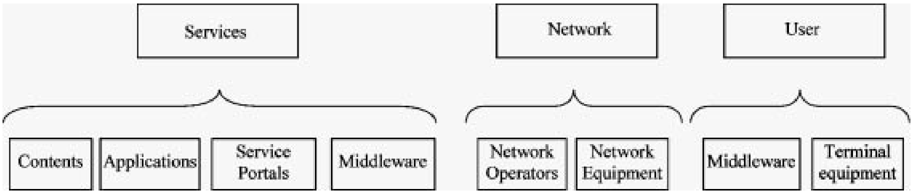

Figure 6.5 3G value chain

- Network: Through the different networks available, users will be able to access all the new services developed using the advanced service capabilities of 3G cellular standards.
- Users: Undoubtedly, the most important part of the business. They will determine which services and networks succeed and which will fail.

The second level of detail consists of the specific players involved in the different processes that form the new value chain. These are the following:

- Contents: Services are initially empty. To fill them, adding some value interesting for the user, content is needed. In general, this content is expected to be multimedia, including video, audio, and text (films, songs, news, video conference) providing support for shopping, banking, games, or even location-based applications.
- Applications: In order to easily access and enjoy the different contents offered over 3G networks, users will require customizable applications running in their mobile terminals and/or in the network.
- Service portals: The amount of services and contents offered in 3G cellular systems will be incredibly high. Service portals will concentrate these services and contents, allowing users to efficiently find and select what they want at any given moment.
- Middleware: Generally middleware is understood as software conceived to connect two or more otherwise separate applications. In 3G and SDR systems, middleware will be required in both the service and user sides of the value chain.
- Network operators: These are the owners of the network and therefore are in control of its exploitation. They usually intend to expand horizontally over the value chain, taking new activities such as service and content provision.
- Network equipment manufacturers: These manufacturers build and provide the equipment required by operators in order to deploy their networks.
- Terminal equipment manufacturers: These manufacturers build and provide the terminal equipment required by end users to access the different networks and services.

As stated above, the ‘contents’ box of the value chain is very important because it adds value to the services offered to the end users. For this reason, in Figure 6.6 this box has been decomposed in a more detailed value sub-chain that allows some different players that had remained hidden in the chain shown above to be identified.

Three new players can be identified in this sub-chain:

- Content creators: These players generate the different contents demanded by the users. Film studios, record companies, and book editors are good examples of content creators.
- Content aggregators: Contents can come from very different sources. Therefore, the role of

Figure 6.6 Content value chain

content aggregators, players that bring together different kinds of contents, is practically indispensable.

- Content providers: Finally, contents created and aggregated must be provided to the end users. These players accomplish this important mission.

Sometimes these three activities can be performed by the same organization. However, it is also possible that three different players may realize the three different activities independently.

The reader should take into account that all the different boxes in the value chain previously proposed can be decomposed into more detailed sub-chains, as has been done for the 'contents' box.

As shown in the previous paragraphs, the advent of 3G will significantly alter the current value chain due to the increasing importance of contents. What will happen when SDR technology becomes a reality? Well, if reconfiguration is added to 3G systems, the value chain of Figure 6.5 will undergo another modification that will especially affect the network side. In effect, if the whole radio system becomes reconfigurable, the network box can be divided into another value sub-chain as shown in Figure 6.7. This new sub-chain looks like the original 3G value chain because it consists of the same kinds of players but at a lower level. This means that these new players will not only provide applications and contents as they did in the 3G model, but also protocols and algorithms destined to reconfigure the lower layers of the radio system (in both network and terminal sides). These new actors are mainly the following:

- Protocol module developers: They will develop software modules such as standard radio interfaces, connectivity protocols (i.e. Bluetooth, IrDA …), etc.

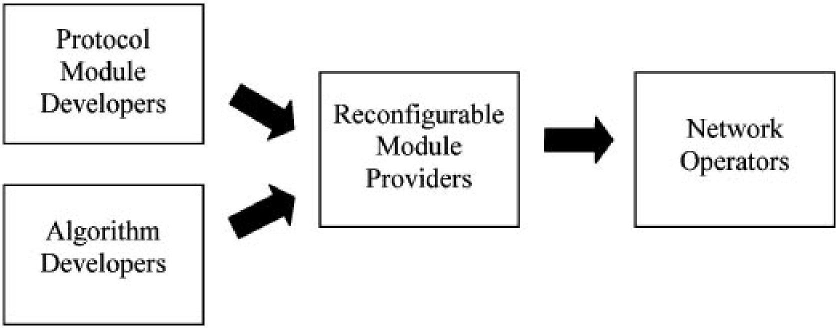

Figure 6.7 Software radio network value chain

- Algorithm developers: They will work in the lower layer of the protocol stack, developing specific algorithms (such as a certain video decoder or a certain encryption procedure).
- Reconfigurable module providers: They will concentrate and integrate the different software modules developed by the two former actors, in order to provide operators (and end users even) with a complete ready-to-use product.

As stated in previous cases, sometimes the same company will cover these three business positions, but in other occasions, three perfectly differentiated actors may exist.

6.3 Operator and Service Provider SDR Requirements

Software radio systems are seen as an essential part of future 3G and 4G wireless systems. Since the enabling technologies for reconfiguration are developing rapidly (i.e. high-speed DSPs, analog/digital (A/D) converters, adaptive wideband antennas, multimedia codecs), it is crucial that detailed user requirements work is carried out before the technology basis is fixed.

As operators and service providers are one of the most important potential SDR user groups, this technology must take into account their requirements in order to eventually succeed. Network reconfiguration capability supposes such a breakthrough that operators cannot avoid raising many questions about this technology and its implications. The most important ones are explained below:

- Definition of a minimum set of bearer services, which should always be available in the reconfigurable terminal.
- Technical aspects, such as the definition of a pilot carrier common to all the standards in order to inform the terminal about which systems are available in a certain geographical area and what their capabilities are.
- Costs. Operators would like to know if reconfigurable systems are going to be more economical than current systems in terms of maintenance. For instance they are interested in comparisons of dual-mode universal mobile telecommunications service (UMTS)–GSM terminals and reconfigurable ones in order to know how the latter could affect (and hopefully reduce) terminal subsidies.
- Access control. It is necessary to determine who can make the decision to initiate, enable, and disable downloads. The network operator should be able to enable or disable the download process after having checked that everything is all right. Network operators need to have the means of enabling and disabling the download in order to protect their networks from any possible failure.
- Authentication of the software module, the hardware module, the user, the originator of the download, and the source of the software being downloaded. All the actors involved in the download process should be identified and authenticated. It is also necessary to check that the software modules to be downloaded have already been validated and licensed. Again, these tasks should also be realized by network operators in order to protect their networks and their customers.
- Capability exchange. The network will have to check that the terminal involved in the download process can be properly configured to receive, accept, install, and successfully run the downloaded code. If it is not, the download process will be immediately disabled. To perform this task properly, network operators will need a standardized set or list containing the parameters and capabilities that have to be checked.

- Safety of downloaded software. The downloadable software modules must be absolutely protected from viruses, bugs, and any other error sources that could harm the network or the terminal during the download process. For this reason, a validation process should be defined and standardized in order to assure that a module is ready to be downloaded. This validation process is probably the most important in the whole reconfigurable system because it guarantees that the software modules provided by different companies are all compatible and do not cause failures in the system. So, new players can enter the market increasing competition and, as a consequence, maximizing quality and efficiency levels. Of course, these validation tests should be the same worldwide in order to guarantee the global roaming capability.
- Reset and recovery in the case where download fails in some manner. In spite of all the security and integrity measures described above, there is still a possibility for the download process to fail. The network and the terminal need to have some procedures or mechanisms that allow them to recover from the failure and to reinitiate themselves without disturbing the rest of the users.
- Billing. In current systems, billing is already a complicated task. However, in software radio systems it will reach increased complexity. Different prices will be applied to different download modalities. Perhaps, it will be attractive to establish the prices attending to a combination of time and traffic criteria. Operators will have to make a big effort to create an appropriate pricing system, but they will not be alone in this process. Agreements between them and the other players in the value chain seem to be unavoidable.
- Responsibility for maintenance. It will be necessary to determine who is responsible for the maintenance of the downloaded software modules. This would seem to be a task for the software providers; however, it will be necessary to establish where the limits of that responsibility reside.
- Write once, run anywhere. This is the aim of software providers and to achieve it, it will be necessary to define a standard interface between hardware and downloadable software that is accepted worldwide.
- Regulation. A global regulatory body would seem to be needed in order to create a unified legal code that should be followed by all the players implied in the download and reconfiguration processes. This code should include the different penalties and sanctions that would be imposed on those breaking the established rules.

Of course, future research work is still needed to further refine these requirements using more complete (and complicated) scenarios. This first list of requirements suffices however to show the reader the complexity of SDR and its implications on cellular networks and terminals.

6.4 Use Cases and Associated Requirements

The utilization of use cases in the development of new communications standards and systems is taking on increasing importance. These use cases describe the interactions existing between the user and the system through a prototypical course of actions along with a possible set of alternative courses of action.

In the development and standardization of software radio systems, use cases can play a fundamental role in gathering user requirements. For instance, the European Union 5th

Framework Programme IST-TRUST project is already employing this methodology in order to drive more detailed UML modeling activities which are being used to represent the functionality and interactions of system modules. In this section, some simplified use cases are presented in order to show the reader some of the new possibilities that SDR will allow.

The SDR Forum, according to the functionality of the modules to be downloaded, has defined three different categories of ‘software download’:

- high-level communications and computing applications;
- download protocol entities for modification or changing of the bearer service;
- low-level signal processing algorithms for modification or changing of the communication physical layer processing.

These three categories can be mapped into their main enabled services and the three associated areas of interest for the operators. These areas are:

- advanced applications
- interoperability
- standard platform development

In the next paragraphs the main requirements of each area are discussed. The interoperability between standards will be considered first since this area includes many aspects that are also applicable to the other two areas.

6.4.1 Interoperability

Currently, world mobile communications consist of a mixed bunch of different 1G (AMPS, TACS, etc.) and 2G (GSM, IS-95, IS-136, PDC, etc.) cellular standards. Most of these standards are incompatible, so that roaming between them is not possible at all. The so-called 3G (IMT-2000) was hoped to be the solution to this serious problem. However, it failed in this goal and the reality is that at least three different cellular standards (UMTS, CDMA-2000, and UWC-136) may coexist.

Keeping in mind the radio access system evolution described above, it is clear that the ability to adapt the terminal to every existing standard is necessary to ‘survive’ in this multimode and multiband environment; whilst most users may not be global roamers, the main manufacturers, network operators, and service providers are global suppliers, and from their perspective the increasing proliferation of different standards and product variants is undesirable from an economic and logistical viewpoint. This is an important market driver for the interoperability offered by reconfigurable systems. This interoperability between standards generates a set of advantages for the different actors involved. These advantages include:

- Manufacturers will reduce costs and investment requirements because of enlarging the market (not a few technologies but just one technology platform will be able to deal with every radio access system).
- Users will profit from the enhanced roaming capabilities without changing their terminal. Also it will be easy for them to select the most attractive network (considering costs, quality of service (QoS), offered applications, etc.) from the available set.
- Terminals will be able to incorporate new features dynamically as service technology continues to evolve. This fact makes reconfigurable terminals attractive both to the users and also to the operators, who may be able to reduce their current terminal subsidies.

- Radio transmission characteristics will be optimized according to the environment conditions and traffic demands as well as to the service or application desired, increasing the QoS and making a better use of the available resources.
- Operators will be able to reduce the current churn rate, achieving longer client fidelity.
- Operators will be able to improve continuously their QoS, following the modern business trends of Total Quality Management and Kaizen.

6.4.2 Standard Platform Development

This second kind of reconfiguration affects the lower layers of the protocol stack. Its aim is to improve the processes and operations performed by those layers in terms of quality, speed, cost, and functionality.

Normally, mobile terminals will be provided with a set of basic features. Whenever the user wants to upgrade these features, he will need to download a new software module to his terminal. Furthermore, such download may also be initiated by the network, if it needs to reconfigure some of the terminal features in order to ensure the communication will be completed properly (this will be shown in one of the particular use cases proposed later in this chapter).

Some examples of the downloadable software modules included in this category are:

- a new audio codec incorporating new features such as a higher compression rate;
- a new ciphering algorithm improving the system security;
- a new image compression algorithm with better quality and resolution levels.

These software modules will probably come from different sources. This implies that some validation procedures will have to be established by the operators in order to control the quality of these modules. A complete testing process will have to be completed before downloading these modules through the network.

The new capabilities provided by these downloadable modules can be used by the operators as differentiating factors that allow them to secure important competitive advantages.

Users will add new features to their terminals as they are needed, potentially lengthening their life span. As it was said before, this will also benefit operators because they will be able to reduce the costs of their terminal subvention policy. (Of course, manufacturers will still strive to increase terminal sales, perhaps increasingly selling on the basis of style and fashion rather than technical functionality.)

The requirements for this software download category practically coincide with those of the reconfigurability use case. However, security and validation issues have an even greater importance here, because the software modules belonging to this category affect the lower layers of the protocol stack, i.e. the basis of the whole system. An apparently minor error at this level could be very harmful for the system and hence extreme precautions must be taken.

The fierce competition between network operators forces them to offer something different, something special and useful in order to increase their revenues and market share. Reconfiguration offers the operators the opportunity to provide their users with higher capabilities improving the QoS. This fact can be used as a marketing tool in order to achieve some of the following goals:

- attracting new customers

- providing best customers with premium services
- decreasing churn rate

Therefore, standard platform development becomes an important marketing and value-creating tool that can significantly improve the quality of the services provided by a certain operator.

6.4.3 Advanced Applications

This last area of interest consists of downloadable software modules affecting the upper layers of the protocol stack (i.e. the application layer). Currently, the WAP technology (and also *i-mode* in Japan) is beginning to provide some of these services but in a limited way. Software radio technology will incorporate more powerful features and capabilities extending the possibilities of this kind of download. It will be possible to develop client-oriented services with customizable features. This will allow each user to enjoy services completely adapted to his/her own personal tastes and preferences.

Although the network operator is the most interested party in providing these services, this area will also be opened to external developers, service providers, and value added providers, which will compete with each other to maximize their market share. This variety of players implies the need for validation and testing procedures applicable to the different software modules (as was the case for the other two download categories).

The most interesting application areas that have been identified so far are listed below:

- mobile e-commerce
- mobile e-business/working
- games
- advanced location services:
  - locating a given site
  - locating someone’s position
  - location-based information provision

Of course all these applications will be multimedia, incorporating text, audio, still images, and video.

As was said before, some of these applications are already commercially available by means of the WAP technology. Nevertheless, their features and performance are still far away from their Internet counterparts because of the implicit limitations of WAP.

WAP applications currently find three main handicaps:

- Limited graphical capabilities.
- Interface restrictions, which make applications not always friendly to use.
- Poor interaction. Both client/server and JavaScript approaches are not fast enough and have very limited capabilities.

Terminal reconfigurability, combined with 3G devices and interfaces, will solve all these problems, improving application features dynamically as technology evolves.

Furthermore, these new services will result in an increase in client retention (reducing churn) and also will attract new customers. And of course, terminals will not be plain phones any more but multiservice and multifunction open devices.

New business opportunities arise for external service providers, content providers, and value added providers when users are able to freely access the Internet. This means higher revenues for the network operators because of the increase of traffic and because they will also assume these new roles (content provision and the like). In Japan very significant revenues are being earned by DoCoMo simply by taking a few percent of the service charge from third party *i-mode* service providers, since this is a small percentage of a large overall number.

High-level application download is the category with less security and regulation requirements. The reason for this is that these software modules do not affect the basic layers of the protocol stack and cannot harm the system easily. This fact will facilitate the entry of many new actors in the mobile market value chain as shown in Figure 6.5. Content (creators, aggregators, portals) and application providers will play a very important role in this new market coexisting with traditional actors such as network operators and equipment manufacturers. Security concerns will still have importance, not only for technical reasons (viruses, bugs, etc.) but also to avoid fraud and other illegal activities.

6.5 Example Use Cases and Business Models

In this section some particular use cases of software radio for the mobile telecommunications operator are introduced. Several of them include an ad-hoc business model in order to demonstrate the economic potential of SDR technology.

6.5.1 Interoperability

6.5.1.1 Use Case: Traveling Businessman

Because of global economy requirements, nowadays business people travel very often to foreign countries that sometimes make use of incompatible mobile radio access systems. Let us imagine an executive working for a company that has a certain number of sites in different countries. He constitutes a good example of someone having need of perfect interoperability between communication systems. In the following paragraphs this particular use case will be deeply analyzed in order to identify the requirements of the different players involved.

Our executive wakes up at home and uses his mobile terminal (provided by a certain handset manufacturer) to arrange a number of household tasks like checking the security system, opening the garage door and the like. Of course, this terminal is also used to get fresh news in the morning and the status of the traffic in his daily itinerary to his company's main building. That information is obtained by means of a query to his favorite information provider, which is accessed through his favorite mobile portal. A new tax-computing program is also available there and he downloads it to his mobile terminal to evaluate his annual tax duties later on today. The hiring costs of those pieces of information and this software are automatically charged to his monthly telephone bill. Of course, before the download takes place, the server must have checked if the user is authorized to perform this kind of software download.

When he arrives at the office, he contacts his main collaborators to prepare the agenda for a meeting he must hold abroad this afternoon. Now he employs his mobile terminal as a terminal of the advanced multimedia digital cordless telephone system connected to the company's private automatic branch exchange (PABX). This system was provided either by a telecommunication operator or by an independent installation vendor. Internal multimedia calls do not have additional costs for the company, whilst external ones are charged to the monthly communications bill in relation to the connection time or the amount of traffic generated. In this company, people are especially happy because their terminals' features are updated automatically every day by the communication department downloading the new software modules through the firm's network. These software modules have previously been thoroughly tested in order to avoid bugs and errors that can affect the terminal and/or the LAN integrity.

Our manager starts his journey and his mobile terminal changes his radio access system as soon as it gets out of the cordless operation area. To do this change, the terminal needs to know he is leaving that area and get information about the mobile operators he is now allowed to attach to.

After that, our manager arrives at the airport and, when he boards the aircraft, the private network inside the plane begins to work. The terminal is forced to switch to this network in order not to endanger the flight security. A special radio interface that has been proved to be completely harmless to the instruments onboard is used instead, offering a number of free services to the passenger. Pay per use services are also available, for example, a connectivity service with his domestic mobile communications operator that allows him to either receive or start a communications link from/to an arbitrarily located site. This kind of service may be directly charged to his credit card by means of a secure mobile e-commerce transaction making use of a user certificate included in the mobile unit. Of course, roaming agreements between the different network operators involved in the communication will be required.

After landing, our manager goes to the airport main lounge. As soon as he crosses the boarding gate, his mobile terminal detects that a number of mobile operators are again allowed to provide their services. In order to detect those different operators a common pilot channel (broadcast) shared by all of them is needed. Furthermore, since the different operators are using different radio access technologies, a reconfiguration download will be required to attach the terminal to the most suitable network and start the roaming operation. The downloaded software modules may have been previously validated by the operator in order to guarantee they will not cause any failures in the network and/or in the terminal. As the download process can affect the performance of both terminal and network, reset and recovery procedures must be supported in order to solve any possible problem. Capability exchange between terminal and network can be used to avoid starting download processes that cannot be supported by one of the ends of the communication.

Finally, our well-known manager arrives at the office his company has abroad and his terminal registers again in the cordless local system. The radio access technology is somewhat different from the one used at his home office because of the different regulations in the two locations or the commercial advantage that each solution can have at each site. However, a reconfiguration download is still possible and our manager finally gets a visitor extension in his mobile phone that allows him to contact his colleagues in the new site (again software module validation and access control are required before starting the download process in order to preserve network integrity).

This example shows the great complexity of reconfiguration and software download. All the different actors involved in the wireless value chain want to take part in the business and they all have different requirements and needs.

Nowadays, the demand for interoperability is increasing at a high rate. In the year 2002, 80% of all new handsets may be multimode (but still manufactured with non-SDR technology). Therefore, software radio technology has here a very promising market.

6.5.2 Standard Platform Development

6.5.2.1 Use Case 1: Video Codec Download

Standard platform development can be used by operators to offer their customers attractive new services, decreasing their churn rate and increasing their market share. (Indeed, if regulatory changes mandate open access, such tools will become increasingly important for customer retention.) The use case analyzed in this section is related to this idea. Imagine an operator offering its subscribers a new version of a video codec, available as a downloadable software module.

An algorithm developer (see value chain in Figure 6.7) will generate the codec software module and will provide the operator with it. The operator will have to test and validate it before starting the download process. As it was said before, this validation process must be extremely severe and accurate in order to minimize the possibilities of any error occurring. If the validation process gives a satisfactory result, the operator will license the software module paying a certain amount of money to the algorithm developer. After that, the new codec can be downloaded to the subscribers that ask for it. In Figure 6.8 this simple business model has been represented.

Figure 6.8 Business model proposed for the video codec download service

Imagine the validation process ends without any mistakes and the operator decides to license the new codec. Suppose the price of the license is 2 million Euros. Once the new software has been licensed, it can be offered to the subscribers. The operator decides to commercialize the new software offering two different modalities of payment:

- Pay per use. This modality is intended for those subscribers who want to employ the new codec just occasionally. The price for this modality will be 1 Euro/use.
- Pay a monthly subscription fee. This modality is intended for those subscribers who use the new codec very often. They pay a fixed monthly fee and can employ the codec as many times as they want. The price for this modality will be 6 Euros/month.

Suppose the operator has 10 million subscribers. The penetration rates foreseen for this service are:

- first year: 10% (1 million users)
- second year: 20% (2 million users)
- third year: 30% (3 million users)

The distribution between the two modalities of payment is expected to be:

- pay per use: 30% of the users
- pay per month: 70% of the users

The users having chosen the pay per use modality employ the codec typically three times a month.

With all these suppositions some calculations can be easily made in order to determine when the operator will recover its investment and therefore, when it will begin to profit from the commercialization of the new codec. The revenues of the operator will be:

- first year: 5.1 million Euros/month
- second year: 10.2 million Euros/month
- third year: 15.3 million Euros/month

At the proposed pricing it can be seen that the operator would recover his investment within the first month of commercialization of the new codec. Even at a much lower pricing level the commercial potential can be seen.

This is just one of the many possibilities of improving the standard platform of a reconfigurable radio system. Software download allows implementation of such improvements in a rapid and transparent way. Every customer will be able to choose which features he wishes to add to his terminal according to his own needs and budget.

6.5.2.2 Use Case 2: Capacity Management

Reconfigurability allows operators to achieve increased control of their resources in order to make a more efficient use of them. One of these scarce resources is undoubtedly network capacity. As known, network capacity has always been a key issue for operators trying to offer the best service to their subscribers. In fact, network dimensioning and planning have traditionally required large full time engineering task forces.

In this section an example of how an operator can make use of software radio technology to increase its network capacity is given. Imagine there is a congestion in a certain cell of the network because the users connected to that cell are offering too much traffic collapsing the system. This can happen very often in scenarios such as business centers, large public events (sports, concerts), airports, etc. In such scenarios the operator may wish to increase the local capacity by reducing the bit rate per user by downloading a new codec with a higher compression rate (cf. the Half Rate GSM codec). With this new codec, each user will require less bits per second and new users from this cell will be able to access the network. Of course, if this new codec comes from an external provider, a complete validation procedure will be required in order to preserve both network and terminal integrity. Again, as in the previously analyzed use cases, capability exchange between network and terminal, as well as reset and recovery procedures are required.

The operator will have to take into account that if the use of the new codec supposes a reduction of the QoS offered to its subscribers, these will have to be compensated somehow. A possibility would be to establish different prices for different levels of QoS. Clearly the reconfigurability offered by SDR technology could add complexity to current billing procedures.

6.5.3 Advanced Applications

6.5.3.1 Use Case 1: Games

WAP already allows users to download simple games including some interactive ones such as chess. However, as stated earlier, their technical limitations make them not attractive enough for some users. As new and more complete application download protocols are developed (new MExE classmarks, based on Java), better games will be available and more customers will be willing to pay for them.

Let us imagine how this service could be provided. Suppose the user asks a certain content provider for a new game. He is accessing this provider's web site through his favorite portal using for the connection the network of an operator and his terminal, provided by a handset manufacturer. He can ask for two kinds of games: plain and interactive. If he asks for a plain game, he just needs to download it and after that he can release the connection and start to play. But if he prefers an interactive game he will need to maintain the connection in order to exchange information with the server and with the other participants in the case of a multi-player game.

Of course, this last kind of game is especially interesting from the operator's point of view because it increases the amount of exchanged traffic and extends connection time, generating higher revenues. But also this kind of game will require more network resources, forcing the operator to dimension its networks adequately to provide high data rates and low latency in order to maintain the needed interactivity level. Furthermore, the service platform will need to have some storage capacity to save data that will allow the user to resume a game at the same point where he left it.

As these games usually will come from third parties, they will have to undergo a certain validation process in order to determine that they are clean of viruses and bugs that could affect the network and/or the terminal.

6.5.3.2 Use Case 2: Music Download

Music download is another business area that could have a great impact during the coming years. Imagine a user wants to listen to his favorite song on his way back home after a hard day of work. He has found the song in the electronic catalog of a certain content provider and wants to download it (as in the game use case, he is accessing through a certain portal, over a network property of an operator and using his terminal provided by a handset manufacturer). So he asks for the song by sending a simple query. When the provider receives it, a capability exchange process starts. This process determines that the terminal is not ready for the download because it needs a certain audio decoder (let us say, in current terms, MP3). The user is invited to download this decoder or alternatively to stop the process. Let us assume the user wants to continue with the download process. The provider starts the decoder download and, when this is complete, downloads the chosen song. Finally, the user can listen to the song and relax.

As shown in previous sections, high-level software download involves many different actors creating lots of relations and links between them. These relations will be fairly complicated and many different kinds of contracts, agreements, and liaisons will be established in order to get bigger market shares. Therefore, billing will be a critical point in the provision of these new services. Prices will have to be high enough to satisfy the needs of all the players involved, but also low enough to attract customers.

To demonstrate these kind of services will be economically viable, let us make some suppositions that allow a simplified business model to be established. Imagine a music download service provided by a European operator that has established agreements with the most important record companies (content providers). The songs are codified in a standard format that is understood by all the user's terminals. (This is done to simplify the model. Normally, a special codec will be needed and will have to be downloaded when it is not available in the terminal.) Although other population sectors could also be interested, teenagers and students seem to be the potential users of this service. Nowadays, on their way to school or university, they listen to music using a Walkman and a pair of earphones. They usually take a mobile phone with them as well. So, if they could have both things in just one terminal and with digital quality, they would be delighted. Furthermore, they could choose the songs they want to listen to, which makes the service even more attractive.

Let us suppose a potential market of 3 million people (aged 14–25). The estimated penetration rate of this service will be 20% the first year growing up to 60% in 5 years time. The user will have to pay a fixed monthly subscription fee. The revenues proceeding from this payment will go directly to the service provider. Besides, the user will pay for the traffic he generates and this money will go to the network operator. In Figure 6.9, a scheme of this business model has been represented, including the relations existing between the different actors involved.

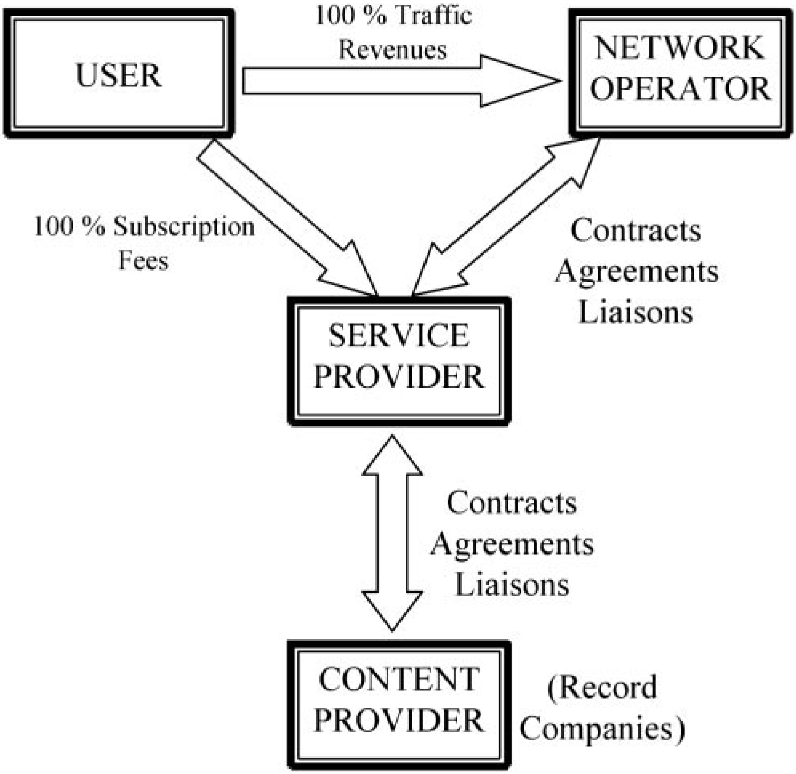

Figure 6.9 Business model proposed for the music download service

The prices foreseen for this service could be:

- monthly subscription fee: 7.5 Euros
- number of bus/train/underground trips: 2 a day, 5 days a week

- average trip duration: 30 min
- average number of downloaded songs: 5 songs/trip
- average download time: 20 s/song
- connection price: 0.3 Euros/min

Assuming these prices and the penetration rates mentioned before, the operator monthly traffic revenues will be:

- first year: 14.4 million Euros
- fifth year: 43.2 million Euros

And the service provider monthly revenues will be:

- first year: 4.5 million Euros
- fifth year: 13.5 million Euros

Of course, this is a limited model and could be improved by adding new factors and players. Although the pricing and suggested subscriber numbers could be debated and changed, and indeed will vary between country and culture, the model provides an indication of the business potential offered by such services and the role within this that software radio could play.

6.6 Conclusions

The advent of cellular communication systems boosted the world economy spectacularly, facilitating new ways of working for existing business and then creating flourishing new markets. These markets continue growing today, incorporating new services and applications that attract an increasing number of market segments.

The arrival of 2.5G and 3G cellular standards will significantly modify the way people use mobile networks. Data traffic will increase considerably thanks to applications such as web browsing, e-mail, e-commerce, interactive games, etc. A lot of new actors will enter the cellular market, enlarging and altering the current value chain.

However, 3G systems may not solve some chronic problems of mobile communications such as the existence of different standards in different parts of the globe or the short lifetime of the mobile terminals used (becoming rapidly obsolete). And here is where software radio technology has much to offer.

The introduction of reconfigurability in cellular networks and terminals will also modify the existing value chain, creating new important roles. The relationships between the different actors involved (traditional and emerging) will be extremely complicated, including different kinds of contracts, agreements, and liaisons. Regulatory authorities all over the world will find here a hard job to do: establishing a regulatory framework that includes a wide range of new business possibilities.

In the definition and development of a new standard technology, user requirements should always play a crucial role. This idea is also applicable to the development of software radio. The potential users of this technology (mainly operators and end users) have a set of requirements and needs that must be taken into account in order to develop a really useful and satisfactory technology.

In this chapter, a first set of general requirements has been given, including the following:

- existence of a minimum set of bearer services supported by all the software radio systems (i.e. a common pilot channel);
- access control and authentication of all the actors involved;
- capability exchange between the different entities involved;
- integrity of downloaded software;
- existence of reset and recovery procedures;
- billing aspects;
- responsibility for maintenance.

Three software download categories must be considered when analyzing software radio market opportunities. These categories are:

- high-level communications and computing applications;
- download protocol entities for modification or changing of the bearer service;
- low-level signal processing algorithms for modification or changing of the communication physical layer processing.

The first category allows advanced applications to be downloaded to the SDR handset. To illustrate this, two particular use cases were proposed. Games are seen as one of the possible killer applications in 3G and beyond cellular systems. Music download is also creating a lot of expectation. Here, a simple business model was proposed in order to show the economic potential of this kind of service.

The second category is related to the download of new radio interfaces to the SDR equipment. This kind of download will allow SDR users to freely roam all around the globe employing only one mobile terminal. This interoperability will also benefit operators and manufacturers, increasing wireless market efficiency. A use case describing how a traveling businessman can profit from SDR technology was presented in this chapter.

Last but not least, the third category has to do with modifying the lowest layer of the protocol stack. Both operators and end users will be able to download software modules that allow them to improve the standard capabilities of their SDR equipment. As examples of this kind of download, two use cases have been proposed in this chapter. In the first one, a user required to download a new and more advanced video codec. In the second, a network operator decided to download a more efficient voice codec to some of its subscribers in order to create increased localized network capacity.

In summary, it can be concluded that the introduction of software radio technology could provoke a revolution in the wireless market, deeply altering the current business structure (new value chain, new services and applications, new business models).

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[2] International Data Corp., www.idc.com

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Part III

The Global Context

7

Reconfigurable Radio in Europe

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[a] *Siemens AG*
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Commercial drivers for software defined radio (SDR) in Europe and North America are quite different [1], arising from differing market maturity and environment in both regions.[1]

The multiplicity of standards and the later migration from analog to digital in the US, compared to Europe, created a perceived market opportunity for reconfigurable base stations, although the market structure has in fact made it difficult for technology pioneers to access this market. Nonetheless, concept feasibility was demonstrated which has motivated further investment in a geographical region where venture capital is freely available.

In Europe, by contrast, the market driver has been perceived to be not second- (2G), but third-generation (3G) personal communications, with reconfigurable radio initially perceived as a potential solution to the difficulty of securing a single global air interface standard. This, matched by concerns that North America could not be allowed to pursue software radio unchallenged, resulted in the inclusion of a category specifically addressing software radio in the ACTS (Advanced Communication Technologies and Services) Second Call for Proposals and in subsequent IST (Information Society Technologies) research supported by the European Commission from 1997 to 2001, as described later in this chapter.

In Europe, it is argued that the significant near-term impact of reconfigurable radio will be in the field of service and applications innovation, using software applications download as a tool to allow rapid and flexible service customization and new degrees of operator differentiation. This situation reflects the relative maturity of the personal communications and digital broadcasting markets in Europe, compared to North America. It is likely, that the requirement for roaming across differing air interfaces can be more effectively met, at least in the short term, by means of SIM card roaming. It can be argued that such developments are likely to be paralleled by an acceleration of software radio technology development in the next few years aimed at allowing manufacturers to address the market discontinuity represented by the introduction of 3G (universal mobile telecommunications service (UMTS)) in Europe.

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[1] This is reflected even in the terminology, such that in Europe the term ‘reconfigurable radio’ has emerged as the more commonly used phrase, with somewhat different meaning, as explained later.

Technology research and development (R&D) supported by the European Commission [2] considers this analysis when defining new programs. A perspective is described on the status and development of reconfigurable radio in Europe, focusing upon the impact of such differing regional influences and exploring the drivers of reconfigurable radio, from a European perspective. The significant role of the European Commission and relevant projects of the RACE, ACTS, and IST program are presented, which have been established within the collaborative European R&D framework, providing pointers to sources of further detailed information.[2]

7.1 The European Context of Collaborative R&D

7.1.1 Emergence of the 'Reconfigurability Perspective'

For over a decade a key role of the Directorate General XIII of the European Commission, latterly DG INFOSOC, has been to instigate and coordinate leading edge R&D in telecommunications, via the multi-year, so-called, Framework initiatives, which have included the RACE, ESPRIT, ACTS, and IST programs. Over this period, Framework has been instrumental in creating a culture of collaboration across national cultures and boundaries and between strong and independent competitors, by maintaining a long-term R&D focus, but with strong industry involvement.

In the field of reconfigurable radio systems and networks, the European Commission has played an important driving role. Activities supported by the Commission focus on the overall perspective of reconfigurable systems rather than on specific leads in some technology areas. At the present time several projects are in hand which are to varying degrees yielding technical results of relevance to reconfigurable radio.

From a European perspective, 3G personal communications has been a long time in gestation. Early work first began, under the auspices of the European Commission's RACE program, as far back as 1986, with the original RACE Mobile Project which developed system concepts and initial spectrum estimates, which subsequently fed into the ITU WARC, eventually leading to the allocation of spectrum for 3G. This project was followed, under RACE II, by others addressing network issues (MONET) and exploring time division multiple access (TDMA) and code division multiple access (CDMA) air interface technology options (ATDMA and CODIT, respectively) and culminated in the ACTS FRAMES project (1995–1999) which made major contributions to European Telecommunications Standards Institute's (ETSI's) strategic decisions in January 1998 on the UMTS terrestrial radio access (UTRA).

In 1996, within the scope of the Second Call for Proposals of the ACTS R&D program, the FIRST (flexible integrated radio systems technology) project exploring the possibility of intelligent multimode terminals was probably the first project explicitly recognizable as what has today become known as software defined radio.

In March 1997, the European Commission (EC) organized the First European Workshop on Software Radio [5], in an attempt to increase awareness of the emerging field and to

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[2] This chapter focuses primarily on public domain collaborative research supported by the EU. It does not describe proprietary research undertaken confidentially within individual companies, nor the work of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE [3,4], for its member companies.

broaden the scope of the discussion beyond reconfigurable terminals. Representatives of the (then) MMITS Forum, today the SDR Forum,[3] were invited as key speakers, along with leading authorities from Europe and Japan. The workshop was instrumental in stimulating responses to the ACTS Third Call for Proposals, which included novel technological work in reconfigurable radio technologies. Two projects resulted in this area: SUNBEAM (smart universal beam-forming) and SORT (software radio technology), one dealing with the integration of smart array antennas in a software radio base station, the other looking into baseband issues, specifically channelization. In June 1998 the Commission collaborated again with the MMITS Forum, to organize the First International Conference on Software Radio in Rhodes, Greece, with the objective of fostering the exchange of experience in the field, and explicitly of promoting a broader approach, extending beyond the terminal. Since the ETSI 3G decision in January 1998 to opt for W-CDMA (wideband code division multiple access) for the paired spectrum and TD-CDMA for the unpaired spectrum the activity level in Europe on UMTS research and development has soared – with some of the research addressing the opportunities for reconfigurable radio within the 3G market.

It was from this context, and with the objective of launching a European initiative in this area, with an all-encompassing system-wide perspective, that in March 1999 the Commission organized the First European Colloquium on Reconfigurable Radio Systems and Networks, bringing together experts from many relevant areas, from digital signal processors (DSPs) to smart antennas, from algorithmic research to radio frequency (RF), from middleware and applications to network management.

At the 1999 Colloquium, the Commission proposed a much broader, all encompassing approach than the one they perceived at the time as being espoused by the SDR Forum. The latter’s approach was viewed as concentrating mainly on the terminal, while the new paradigm in the IST program covers the whole system, extending through the network into service creation and application development.

7.1.2 Implications of the ‘Reconfigurability Perspective’

Within the emerging vision, reconfiguring-on-demand is promoted not only for the terminal but also for the serving network(s) and the services they provide (hence reconfigurable radio systems and networks). Upon this open framework, truly ‘platform’-independent applications are envisioned, no longer exclusively developed by or for operators, capable of adjusting themselves to the serving network capabilities (or even being able to select from alternative serving networks) and to the terminal characteristics, negotiating with the network to obtain the best possible service taking into account the user profile. Such an open framework allows for the involvement of new players, resulting in a revamped Business Model; however it also raises serious institutional issues relating to Standardization and Regulation. Reconfigurability would also promote a more spectrally efficient delivery of information to the user, taking into account the observed network traffic/load, and is ultimately seen as the enabler of full spectrum sharing. This, however, raises many issues concerning ‘ownership’ of spectrum, currently treated much like real estate.

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[3] See Chapter 3.

In order for all the above to come to fruition, a number of enabling technologies need to be developed, spanning software, hardware, and algorithmic aspects.[4] And, driving it all, are (quite obviously) economic and business considerations, which have kept reconfigurable radio initially so focused on the short term. However, this bigger picture suggests that there is much more to be gained from reconfigurability in this broader sense, than a terminal-focused perspective would ever allow. Moreover, by identifying the many advantages of reconfigurability at the Application level, and de-coupling them from the need for reconfigurable terminals, we can envision the provision of such enhanced services starting almost immediately and to all terminals, including the many dumb, 'legacy', ones.

Reconfigurability entails, in this wider context, the pervasive use of software reconfiguration, empowering (possibly live) upgrades or patching of any element of the network, and of the services and applications running on it. It cuts across the types of bearer radio system (paging to cellular, wireless local area network (LAN) to microwave, terrestrial to satellite, personal communications to broadcasting) enabling the integration of many of today's disparate systems in the same hardware platform. More importantly, it also cuts across generations (second to third to fourth). It cannot be conceived as just a way to implement 3G, ignoring 2G and compromising the potential of 4G or, even more short term, just to solve the multimode problem. Conversely, it cannot be driven solely by 4G, long-term, considerations.

Reconfigurability is expected to play a critical role in maintaining Europe's leadership in the area of mobile/wireless communications by increasing flexibility; reducing deployment as well as operation and maintenance costs; creating new business opportunities and employment; facilitating enhancements and personalization, etc.

To complete the picture, let us take as a reference point the block diagram of a typical reconfigurable signal processing chain shown in Figure 7.2.

This diagram provides a somewhat simplistic view of a mobile communications transceiver, and can be easily modified to describe a base station. Moving from the antenna/ RF stages towards the baseband (BB) processing part of the transceiver, we progress from a hardware-centric towards a software-centric design. However, let us look at the elements at both ends of the transceiver chain.

On one side, we have the antenna, increasingly integrated with the RF stage. Here, reconfigurability, especially when associated with the use of smart antennas, will permit a more efficient use of the spectrum. On the other, we have the (network) protocols, the application, the man–machine interface (MMI), and ultimately the user. Reconfigurability will allow adjusting the application to the MMI limitations and the user preferences, and for invoking at the network level the necessary adaptation/transcoding. It will also make it simpler to deal with multi-streaming. In fact, multi-streaming can make good use of different bearer channels, in different spectrum bands (e.g. DAB/DVB, global system for mobile communications (GSM)/general packet radio service (GPRS), UMTS).

In the scope of the First Call for Proposals of the IST program in 2000, a series of projects were retained that address this broad concept of reconfigurability. To position these new projects, we cross-reference the 'system' aspects of Figure 7.1, plus the Business Model, with

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[4] These are comprehensively discussed in the companion volume to this one *Software Defined Radio: Enabling Technologies*, Tuttlebee, W.H.W. (Ed.), Wiley, Chichester.

the transceiver subsystems identified in Figure 7.2. Figure 7.3 thus reflects the main research areas of the work of the earlier projects (under ACTS, ESPRIT) and more recent ones in the IST program.

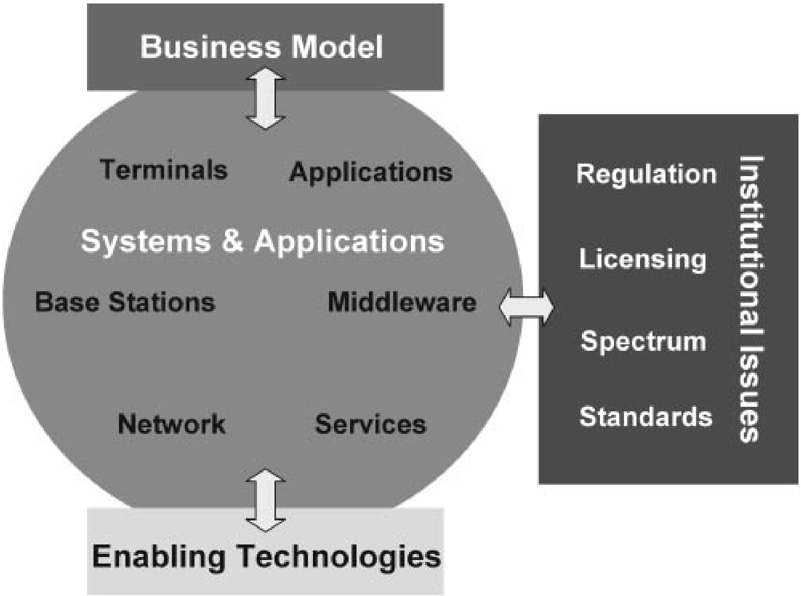

Figure 7.1 Reconfigurable radio systems and networks – scope and function

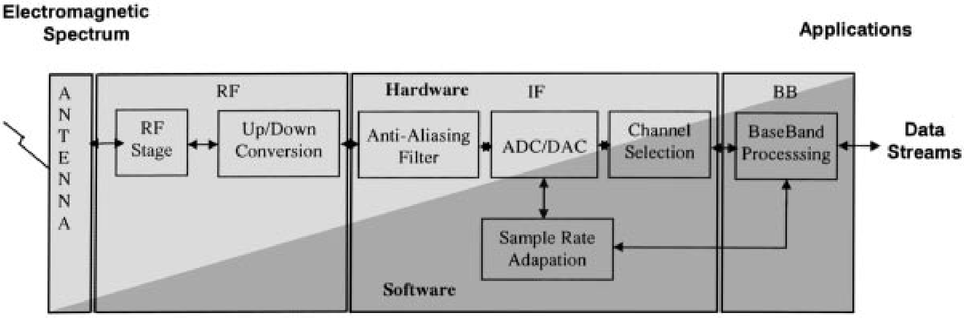

Figure 7.2 Mobile transceiver block diagram

7.2 – 1999: Research under ACTS

7.2.1 Early Work on Reconfigurable Radio

Within the ACTS program, which pre-dated the explicit recognition within Europe of the concept of SDR, the following projects were in hand addressing at least partially some of the

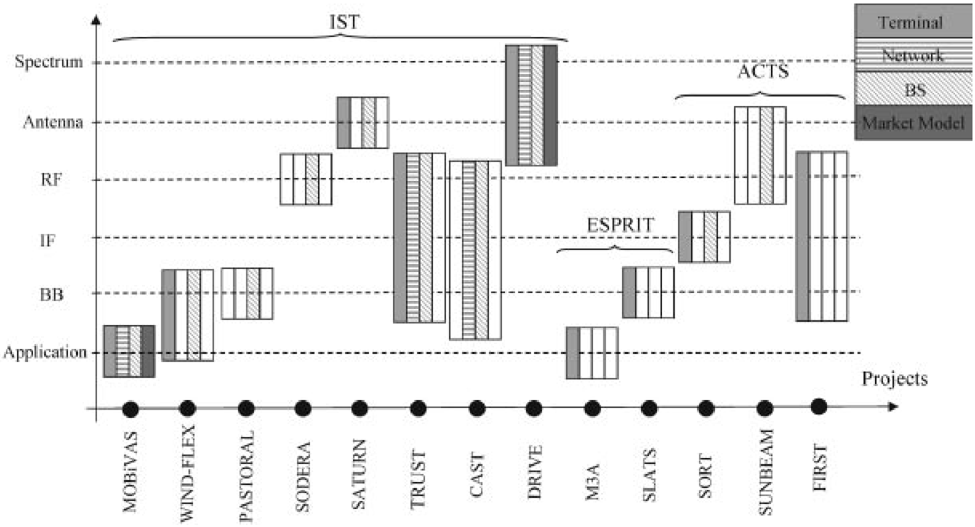

Figure 7.3 Specific European R&D projects in reconfigurable radio

required enabling technologies. Unlike the subsequent IST projects, the ACTS projects did not much consider research issues on business models or SDR network implications.

7.2.1.1 FRAMES – Future Radio Wideband Multiple Access Systems

This large collaborative project, supported by the major European players – Siemens, Nokia, and Ericsson – had as its main goal the audacious objective “to make UMTS happen” [6]. The project focused on the development of air interface technology for the UTRA, and made numerous and substantial contributions to three of the five air interface concept groups established by ETSI SMG in autumn 1997. The ETSI technology decision on UTRA in January 1998 combined the two main technical proposals from FRAMES partners, W-CDMA and TD-CDMA. As well as developing detailed technical concepts, FRAMES also developed software simulations and demonstrator hardware for UTRA. As such FRAMES served to provide experience in the processing complexity and implementation aspects of UTRA on a flexible DSP-based hardware platform. In effect, FRAMES was implementing UTRA as a software radio, not to allow multiple standards but because of the necessity to have a flexible platform in advance of full definition of the 3G air interfaces.

7.2.1.2 FIRST – Flexible Integrated Radio System Technology

The FIRST project had objectives primarily and explicitly related to software radio for UMTS/IMT-2000. It aimed to explore technology solutions for UTRA including transmitters, receivers, and flexible signal processors for reconfigurable modes of operation. As well as generic research, developing possible RF and digital architectures, the project also produced a software radio demonstrator aimed mainly at TDMA access schemes [7].

7.2.1.3 MEDIAN – Wireless Broadband CPN/LAN for Professional and Residential Multimedia Applications

The MEDIAN project, unlike the others described, was not explicitly focused on personal communications but rather had as its focus the implementation of a wireless asynchronous transfer mode (ATM) LAN supporting 150 Mb/s [8]. Its relevance to software radio lay in the design of its advanced baseband processor supporting a COFDM air interface. The processing requirements of this application were immense – around 13 GIPS; nearly three-quarters of this requirement was devoted to FFT processing. With hindsight, arguably a key contribution of this project may have been that it demonstrated the potential benefits of marrying custom hardware processor architectures with software implementations to secure optimized overall implementation solutions.

7.2.1.4 SINUS – Satellite Integration into Networks for UMTS Services

The SINUS project focus was the satellite element of the UMTS. Given the potential of soft terminals this project was, inter alia, examining the feasibility of reconfigurable terminals to support this aspect of the UMTS – in particular, work focused upon hardware reconfigurability for UMTS prototypes and terminals. This work reflected the recognition, mentioned above, that the combination of optimized hardware accelerators with software DSP engines can secure significant overall system simplifications and power savings. The SINUS approach took this a stage further by implementing a reconfigurable hardware subsystem, based around an innovative architecture of field programmable gate arrays (FPGAs) and dual port RAMs [9].

7.2.1.5 IBMS – Integrated Broadband Mobile System[5]

The more advanced system concept of using software telecommunications as a means of flexibly configuring the radio channel to support the time-varying bearer channel requirements of multimedia communications was explored within this project, in particular attempting to identify a minimum air interface backbone – a completely separate signaling channel designed solely for connecting to the wireless network and for mobility management. This signaling channel would then be used to set up and tear down a variety of custom air interface bearers on demand, to support the multimedia service required at any specific time. This concept of the ‘minimum specification air interface’ and its relationship to the network and the handset is described in Ref. [10] in some further detail.

In 1998, under the ACTS Third Call, two new projects were initiated – SORT and SUNBEAM.

7.2.1.6 SORT – Software Radio Technologies

The SORT project addressed the key issues of software portability and hardware reconfigurability for UMTS, for both terrestrial and satellite access. In many ways it aimed to build on some of the existing projects described above, notably exploring the issue of the minimum

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[5] IBMS was part of the German national program ATMmobil, rather than part of the EU collaborative programs.

standard functions for the software definable air interface and the identification of air interface functionalities. It sought to classify the latter as *critical* functions (real time) and *common* functions (non-real time). Demonstration and performance/complexity trade-offs within such a framework were considered [11].

7.2.1.7 SUNBEAM – Smart Universal Beam-forming

The SUNBEAM project sought to explore the already acknowledged synergies between software radio base station architectures and steerable array antenna systems for 2G and 3G digital cellular systems [12]. As such it built on earlier RACE and ACTS projects which had developed steerable array demonstrators based around digital enhanced cordless telecommunications (DECT) technology.

Two other relevant projects were also commenced, in January 1998, under the auspices of the ESPRIT program, SLATS and PROMURA, and ran for 2 years duration.

7.2.1.8 SLATS – Software Libraries for Advanced Terminal Solutions

This project was developing software libraries for 2G and 3G systems [13]. The project had a clear commercial focus, with the objective within this aggressive time scale being to develop a comprehensive library of software modules which could be compiled to run on a variety of hardware platforms. It clearly demonstrated that such a requirement is non-trivial, identifying the complex realities of what sounds a simple concept.

7.2.1.9 PROMURA – Programmable Multimode Radio for Multimedia Wireless Terminals

This project was addressing a range of the less-fashionable, but vital, technology issues associated with the RF content of reconfigurable radio. Its objective was to develop a prototype programmable wideband RF system and to drive technology development associated with this, in particular exploring the process impact with respect to BICMOS and Bipolar SiGe. The project aimed to accommodate operating frequencies from 500 to 2500 MHz and 6 MHz channel bandwidths, validating critical building blocks and feasibility of the complete system [13].

7.2.2 Preliminary Themes – Network Implications

In the ACTS program, research into reconfigurable mobile communications was predominantly focused on early concepts of software radio, and specifically on the hardware technologies required to move physical layer processing into a programmable environment. Although an interesting and necessary challenge, this only represents a fraction of the overall support and technology required to realize the full potential of the concept. The main issues explored within ACTS R&D projects, within the public domain, included:

- architectural and algorithmic implications of reconfigurable radio combinations with other advanced functionalities, such as beamsteering;
- evolution of baseband architectures, to achieve an effective hardware/software balance in

signal processing implementations – e.g. hardware acceleration engines and the possibilities for dynamic hardware, as well as software, reconfiguration;
- evolution of new RF architectures and process technologies to meet the needs of software radio;
- development of tools, libraries, and environments to support software portability.

Even a cursory consideration of reconfiguration will show that its potential ranges far beyond the solution of ‘black-box’ internal problems of the software radio air interface. This somewhat narrow perspective of reconfigurability stemmed from the military origins of the technology that, rightly, focused on multimode terminal and air interface capabilities for voice and low-rate data. Clearly, this is not the vision of commercial wireless communications for the twenty-first century as illustrated in Figure 7.4 [14].

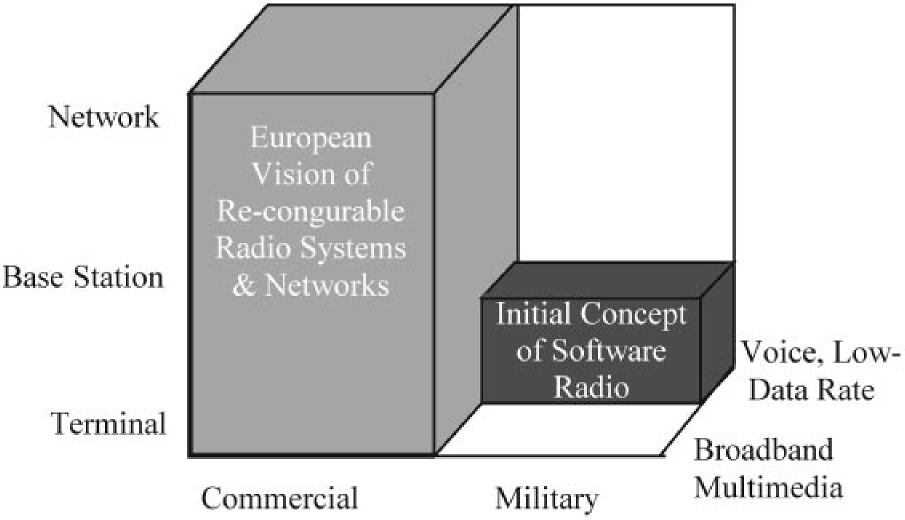

Figure 7.4 Relative positioning of European initiative on ‘reconfigurability’

Reconfigurability offers the Information Technology and Telecommunications world unique opportunities to:

- future-proof new systems with evolving technology, whilst adding flexibility to current ones;
- accommodate changes to customer demands and create new service and application opportunities, markets, and value added chains for service and content providers;
- empower the commercial integration of many competing systems on the same platform;
- encourage integration of successive generations of technology and to ease migration between standards;
- allow the radio access characteristics to be optimized for best transmission performance;
- open the door to spectrum resource sharing between applications and users;
- create opportunities for system and network operators and manufacturers to cut costs.

Clearly, the commercial exploitation of reconfigurability demands a network management vision with seamless connection between heterogeneous network components and transparency through them. Equally, the above list raises new issues regarding spectrum regulation, operator licensing, and standards definition.

Today, commercial wireless network operators, constrained by long-term investment, are facing a thorny problem. How do they optimally exploit their existing networks while evolving towards and deploying reconfigurable solutions? Such an evolution assumes that an intelligent network approach has taken into account the requirements of reconfigurability (signaling and addition of intelligence at the network element level). Thus, the network infrastructure must:

- increase the capability and versatility of networks through the support of terminal reconfigurability;
- facilitate self-planning and self-configuration.

Further, as the evolved market model shows, the network to services interface will likely be multi-dimensional in terms of service and content provider, and number of vendors.[6] Therefore, the network must adapt to a variety of service interfaces and support billing mechanisms for users, intra-operator and inter-operator transactions, as well as content providers. Increasing recognition of such needs, as European R&D progressed in the late 1990s, contributed to the research directions which followed.

7.3 2000 and Beyond: IST

With the start of new projects in the IST program in 2000, projects such as TRUST, MOBIVAS, and CAST[7] have taken into account the outcomes of recent standardization in fora such 3GPP and the IETF and the conclusions of the First European Colloquium. This led to the emergence of new research areas within what has become the reconfigurability domain of the IST program.

7.3.1 Key Reconfigurability Research Projects

7.3.1.1 CAST – Configurable Radio with Advanced Software Technology

CAST [15] aims at laying the foundations for intelligent and adaptable configuration of the physical layer in wireless communications links, enabling users to access customized services over networks operating with different radio standards across different frequency bands. It targets implementation of the protocol stack by proposing a three-layer (management, procedural, physical) reconfigurable architecture to provide the interface between the application and the underlying physical layer of the terminal processing platform. It is building a validation platform to assess the operation of the proposed architecture for the delivery of selected user services.

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[6] Chapter 6 explores further the network operator view and such anticipated changes to the value chain.

[7] The companion volume, *Software Defined Radio: Enabling Technologies*, contains chapters authored by key individuals participating in many of these ongoing programs, providing detailed insights into the technology emerging from this research.

7.3.1.2 DRiVE – Dynamic Radio for IP-services in Vehicular Environments

DRiVE [16] aims at developing methods for dynamic frequency allocation and for coexistence of different radio technologies (so-called 'dynamic radio') to increase spectrum efficiency and reach. It will develop an IPv6-based multi-radio infrastructure to ensure optimized interworking of cellular and broadcast networks for the provision of adaptive high-quality multimedia services specifically for vehicular environments.

7.3.1.3 MOBIVAS – Downloadable Mobile Value Added Services through Software Radio and Switching Integrated Platforms

MOBIVAS [17] aims at developing architectural approaches for integrated software platforms and systems, adaptable to different network services and technologies, which will open new opportunities for advanced value added service (VAS) providers, and at developing innovative and modular network components for seamless and efficient service provision, enabling downloadable SDR value added services. It is combining wireless technology with common object request broker architecture (CORBA)/TINA principles and with sophisticated quality of service (QoS) mechanisms.

7.3.1.4 PASTORAL – Platform and Software for Terminals: Operationally Reconfigurable

PASTORAL [18] aims to develop a reconfigurable real-time platform for 3G mobile terminal baseband development, using FPGA devices developed through a new co-simulation, co-design, methodology which permits an accelerated design cycle. It is also exploring downloading applications and protocols over the air for reconfiguration.

7.3.1.5 SATURN – Smart Antenna Technology in Universal Broadband Wireless Networks

SATURN [19] is researching adaptive/smart antenna techniques, on both the terminal and the base station, for outdoor (UMTS) and for local/campus area wireless networks (HIPERLAN), aiming to promote high bit rate wireless services as well as to provide enhanced location information for location-based services.

7.3.1.6 SODERA – Reconfigurable Radio for Software Defined Radio for 3G Mobile Terminals

SODERA [20] aims at defining and validating the feasibility of the RF architecture best suited for reconfigurable radio taking into consideration the terminal constraints of low power consumption, low cost, and small form factor, as well as at studying the optimum partitioning between different technologies (BICMOS-SiGe, SOI, Micro-Machining). Advanced RF libraries will be developed in order to validate this approach.

7.3.1.7 TRUST – Transparently Reconfigurable Ubiquitous Terminal

Starting from the user requirements from the perspective of the terminal, TRUST [21] investigates enabling technologies such as analog signal processing, adaptive baseband processing, novel transceiver algorithms, and smart power management. It also investigates important system aspects such as spectrum sharing techniques, multimode monitoring, intelligent mode switching, and software download including security issues. Within the wider context of the emerging network scenario, described in Section 7.3.3 in this chapter, the project also seeks to rationalize the 'seamless wireless utopia' by studying the real user requirements for reconfigurable terminals and then creating realistic working scenarios.

7.3.1.8 WIND-FLEX – Wireless Indoor Flexible High Bit Rate Modem Architecture

WIND-FLEX [22] is investigating a high bit rate adaptive modem architecture, configurable in real time, for indoor single-hop, ad-hoc networks, concentrating on algorithms, protocols, and RF/IF subsystems.

7.3.2 The Reconfigurability Cluster

7.3.2.1 The Cluster Concept

The IST program encourages the interaction of its research projects through 'clustering' and 'concertation' activities. The goal is that rather than operating as independent activities, through interaction and information exchange the overall outcome can become more than the sum of the parts.

Thus, the IST work program 1999 [23] states:

> "Clustering" will be used to focus, co-ordinate and integrate the results and on-going work of projects. Clustering activities will not be imposed on projects. The aim is to reinforce the complementarity of projects and the synergies derived from their work and to create a critical mass of resources focused upon issues of strategic importance. Projects will either themselves initiate clustering activities or will find it to be "in their own interests" to support certain initiatives taken by others.

Clusters can be seen as a special kind of concertation activity which have the aim to *create a critical mass of resources focused upon issues of strategic importance*. Complementary to clusters, concertation activities have to manage the 'day-to-day' work needed to guarantee a successful cooperation amongst projects. This includes, for example, the organization of joint workshops and conferences as well as the provision of a forum for the exchange of information amongst projects.

7.3.2.2 Content and Objectives

Taking into account the IST projects working on reconfiguration, the following research areas were identified, which formed the basis for a reconfigurability cluster proposal, with research areas on:

- requirements – service provider and user requirements assessment for multimedia including demands on reconfigurable networks and terminals;

- system concepts – for reconfiguration of networks and terminals;
- enabling technologies – including technology requirements on reconfigurable networks and terminals.

The objectives of this collaborative work among these projects are:

- to establish common ideas and architectures enabling reconfiguration;
- to define concepts for security mechanisms across all open systems interconnection (OSI) layers;
- to agree on software design modeling, e.g. unified modeling language (UML);
- to assess the requirements on enabling technologies;
- to allow the seamless transition and service provisioning across heterogeneous access networks by reconfiguration;
- joint dissemination of clustering results, e.g. as contributions for workshops or standards bodies.

The reconfigurability cluster is intended to progress technical issues in areas where joint effort is useful or essential. It is envisaged that these clustering activities on reconfigurability will be later merged with the other IST clusters ‘Systems beyond 3G’ and ‘Smart Antennas’.

The projects contributing to the reconfigurability cluster aim to foster cooperation among the projects and to develop a vision of reconfigurable systems by describing evolutionary scenarios based on existing systems and revolutionary scenarios deploying leading-edge technologies. Current research areas of IST projects dealing with reconfiguration are defined enriched with the current trends experienced in the research and standardization communities. The projects give their vision on future scenarios and open issues to be addressed in future European Union supported projects or elsewhere. All research topics inherently bear the open point as to what extent SDR concepts need to be standardized and what can remain proprietary, i.e. the responsibility of a manufacturer, operator, or third party. The projects are aware of the ongoing discussions in mobile execution environment (MExE), SDR-F, OISP (formerly OSA), etc., but until now no standardization body systematically addresses the questions to be tackled.

The first research field in which the projects have agreed to cooperate seeks to determine the user and service provider requirements for reconfigurability by introducing a methodology to understand and to promote the demands on such systems. This important input for the complete research field must be understood at first before designing any concepts or developing any technology. For this area a discussion between end user, operator, and manufacturer must lead to a common understanding of the real needs.

The second field is the definition of a worldwide accepted system concept which can be only established by standardization across the network and terminals. The understanding of an architecture enabling a Distributed Processing Environment and the methods for spectrum sharing, mode detection, seamless service provision by mode switching, and the secure software download lead to combinations of the currently defined methods known from classical mobile radio design and computer science. From this synergy will emerge many novel concepts, but also new questions currently not yet formulated. However, it is only by developing a full understanding of these hitherto more or less independent research fields, and of the real user needs, that the full potential of SDR technology will be realized.

The third field, enabling technologies for reconfigurability, addresses the analog RF domain, baseband technology, and the needed programming languages for the software running on the processor platforms. This field encompasses many aspects which can be categorized as proprietary, i.e. manufacturer dependent. It is to be noted that a programming language itself might be proprietary but its classification according to concurrency, persistence, and distributed needs to be commonly adopted and, in this respect, it is a part of the overall system concept.

7.3.2.3 Shared SDR System Concepts

The SDR system concepts reflect other future concepts, for example, the fact that all information devices will be globally connected. Today, we are on the way towards an Information Society. Not only computers, but also, for example, home appliances and cars may be regarded as information devices. These devices will become more and more intelligent and they will be able to provide services seamlessly over a global network infrastructure to which they connect. Mobile and wireless communication systems will play an important role in this scenario. The expanding deployment of these technologies requires continuous R&D activities to enhance the information and communication infrastructures of today, and to build the next generation of networks which are able to meet the requirements of the future. These activities need some common orientation and a shared understanding amongst the key actors involved, in order to develop appropriate solutions and to create the critical mass which supports the successful adoption of these solutions. Such an orientation can be given by a vision which shows a path towards future information and communication systems without the need for complex technical details and, thus, allows the adaption and adoption of new evolving and emerging technologies. Software defined radio concepts also form part of future networks which may be called ‘Systems beyond 3G’. However, for economic reasons of cost-effectiveness, such concepts must be backwards compatible to 2G and 3G systems.

7.3.3 Emerging Themes

As we look beyond the 3G of mobile communications, we initially perceive the convergence towards an IP-based core network and ubiquitous, seamless access between 2G, 3G, broadband, and broadcast wireless access schemes, augmented by self-organizing network schemes and short-range connectivity between intelligent communicating appliances. In this ‘composite radio environment’ where several highly standardized legacy radio transport schemes exist, the medium-term goal would be to develop reconfigurable network and terminal techniques to enable interworking and so to deliver diverse and exciting applications using the most appropriate radio access scheme(s). Appropriate in this sense refers to the dynamic choice of access scheme(s) to achieve seamless, uninterrupted delivery to the user, customized to the user needs in terms of content, QoS, and cost.

7.3.3.1 Embedded Network Reconfigurability

In such an environment, vertical handover may take place between different access systems (cellular layer down to personal network layer, e.g. Bluetooth), combined with real-time service and resource negotiations to seamlessly achieve desired QoS. The interworking, mobility management, and roaming would be handled via the medium access systems and the IP-based core network.

Reconfigurable systems must be embedded into a network environment composed of legacy PLMN networks and future networks based on IP transport mechanisms as illustrated in Figure 7.5.

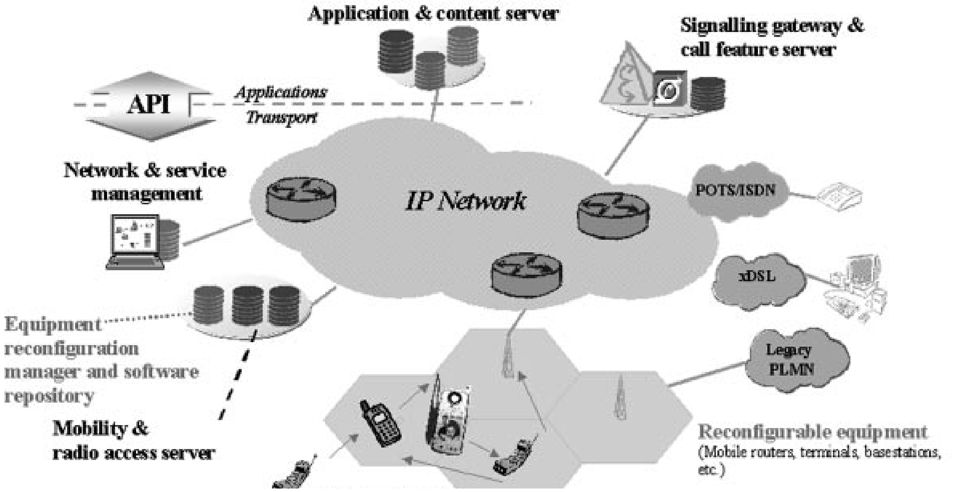

Figure 7.5 Convergence in telecommunications

7.3.3.2 Open Services

The exploitation of 2G cellular networks has been essentially based on voice services in spite of their native capabilities to handle several modes of data services. Thus the common mobile network operation has been offered under a closed model. Nowadays however a revolutionary change of this model is changing this scenario. Alternative service capabilities like short message service (SMS) have grown very quickly and, whilst wireless application protocol (WAP) has seen limited initial success, the introduction of GPRS capabilities will accelerate the use of such new mobile services which offer the opportunity for open, third-party, provision. All these trends indicate that a radical change in the provision of mobile services has begun. The reconfigurable radio concept embraces such new capabilities and extends them to cover more challenging possibilities including the dynamic adaptation of the communication protocol stacks or even the redefinition of the physical layer of the PLMN.

7.3.3.3 Reconfigurable Equipment

Mobile operators and manufacturers will exploit reconfigurable equipment for three main purposes. First of all, these techniques promise a reduction in the costs of mobile communications provisioning. This reduction may come chiefly from the capability of the systems to adapt to support the improved capabilities that are continuously appearing in the mobile arena. Reconfigurable equipment may allow, for instance, to provision the newest voice codecs to older terminals enabling the improvement of either the speech quality or the network capacity. The second role of reconfigurable equipment is related to the imminent need to deploy new networks to exploit 3G wireless communication systems based upon the UMTS standard. The licensing stage is now virtually completed in Europe and networks are already being deployed. Such deployment will require extensive investment in new equipment; the technical merits of the solutions proposed by the different providers will offer scope for differentiation in this market. Thirdly, reconfigurable equipment offers a strategic impact related to the positioning of the network operator and service providers in the new value chain.[8] The new service provisioning chain has an open character, and new business opportunities are anticipated. Market demand and acceptance for such opportunities is still uncertain but IST research dealing with reconfigurability will provide valuable technical foundations for the service provisioning models as well as an indication of the likely time required for such solutions to transition from development laboratories and come to market.

7.4 Future European SDR Research

7.4.1 Objectives and Key Issues

As technology rapidly evolves the likelihood of multiple standards and proprietary enhancements covering all protocol layers increases. Standardization effort is currently concentrating on compatibility questions and mostly precludes mechanisms on negotiations between terminal and network. With a greater variety of interconnected networks in the future, standardization must be shifted to standardized protocol negotiations which provide the mechanisms needed to enable standardized, and possibly new, communication protocols to be established and agreed between terminal and network. This could also imply the introduction of an etiquette between communicating entities.

This stringent demand must be seen against a background that the Internet paradigm moves to the mobile networks and that the evolution of mobile networks reflects a synergy of reconfiguration principles and the IP paradigm. As noted earlier (Figure 7.5), such an evolution of telecommunications in the next decade will be characterized by the convergence toward an IP-based core network and ubiquitous seamless access (2G, 3G, broadband, broadcast …) in a context of hierarchical and self-organizing networks, with interworking, mobility management, and roaming handled via the medium access systems and the IP-based core network. Reconfigurable radio terminals and new appliances will be key components of such a seamless network convergence. In principle, main fields anticipated to form the focus of future research are explored below.

Key issues for future research, within the context of SDR and reconfigurable terminals beyond 3G, have been identified[9] as:

- SDR business models: why, when, how, what for?;
- regulatory issues: spectrum management and sharing, authentication and verification of software, compliance of SDR terminal to regulatory directives;

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[8] See Chapter 6.

[9] These issues are those identified by the TRUST project and thus perhaps reflect a partial perspective.

- radio resource management: spectrum management, vertical handover management, handover procedures and mobility management, dynamic and flexible spectrum allocation;
- user perspective: user requirements, user interactions with the terminal, user profiles, reconfigurable service provision, scalable applications, mobile agents, value added service provision;
- system level issues: novel signaling mechanisms, interactions between terminal and network, system architectures, hierarchical and decentralized network architectures, networks procedures for terminal reconfiguration, intelligent networks, distributed processing, adaptive protocols, software development and validation, mode switching negotiations, software downloading traffic impact;
- enabling technologies: novel RF hardware architectures, reconfigurable baseband software architecture, software download and repository techniques, middleware, application programming interfaces (APIs) definition, reconfigurable signal processing algorithms, adaptive air interfaces, object-oriented software engineering, novel hardware–software co-design methodologies, high performance DSP, reconfigurable logic, tunable RF components, power management.

The above inventory is not exhaustive, and it is fundamental to realize that the definition, design, and development of SDR will require huge amount of effort and research at all levels, to achieve the success of this promising communications evolution. Some aspects of this inventory have already begun to be addressed and are summarized in the next section.

7.4.2 Current Research Status

7.4.2.1 Terminal Reconfiguration

The main advantages of reconfigurable terminals, already discussed, are summarized in Figure 7.6.

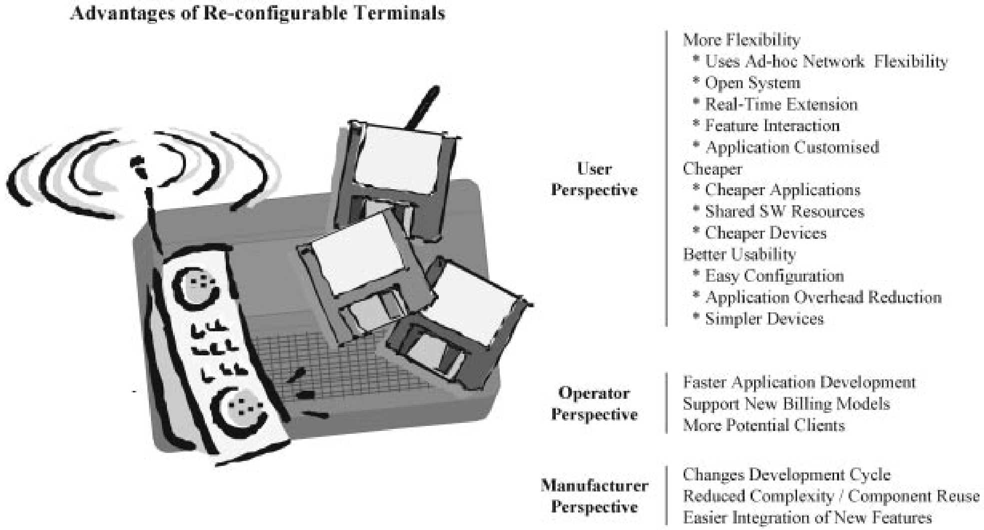

Figure 7.6 Advantages of reconfigurable terminals

System and technical analysis realized in the field of the terminal reconfiguration addresses mainly:

- blind and assisted radio access mode identification;
- radio access mode negotiation and switching management or vertical handover;
- secure software download including authentication, capability exchange, and integrity assurance;
- radio resource dedicated to software download;
- standardized negotiations methods between user, terminal, and network;
- minimal set of terminal and network functionalities to be standardized as, e.g. reset and recovery procedures for terminals.

7.4.2.2 Network Procedures and Architectures

System analysis addresses mainly:

- manageable mass upgrade of terminals combined with a guaranteed QoS for software download;
- procedures allowing spontaneous interaction between terminals and networks;
- adequate handover and mobility procedures for reconfigurable terminals;
- managing upgrades in ad-hoc, meshed, and cellular networks.

7.4.2.3 System-level Modeling

The overall coherence of studies at the system level is ensured by using unified modeling language (UML) and specification description language (SDL).

The top-level use case diagram (UCD), capturing all systems interactions is depicted in Figure 7.7.

Derived from this top-level UCD are defined:

- detailed UCDs
- class diagrams
- collaboration diagrams
- message sequence diagrams
- state transition diagrams

Unified modeling language is used to support the system architecture definition and the detailed design of modules in terms of functionalities and interactions. Specification description language is also used for specific modeling schemes.

7.4.2.4 System and Network Architectures

A network-centric architecture (Figure 7.8) involving the association of a home reconfiguration manager (HRM), a serving reconfiguration manager (SRM), and a proxy reconfiguration manager (PRM) has been developed by the TRUST project. This architecture is useful for cellular networks and provides a centralized software distribution. Concepts have been developed for supporting a decentralized distribution from terminal to terminal suitable in ad-hoc networks.

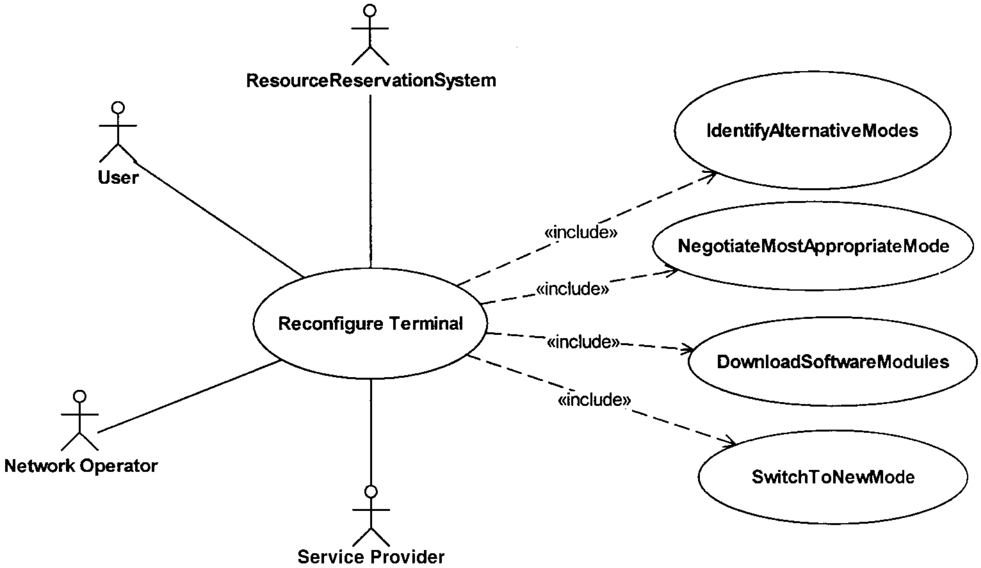

Figure 7.7 Reconfiguration top-level use case diagram

Interactions between terminal and network are crucial as the available bandwidth on the wireless link is a limited resource that should be used for services rather than negotiations. Furthermore, resources on the terminal itself are usually also limited. In order to relieve the terminal from the burden of frequent interactions with network entities, information from the network could be generally obtained via a PRM, located in the radio access network, serving as a proxy instance for negotiations with other network entities, in particular the SRM and the HRM.

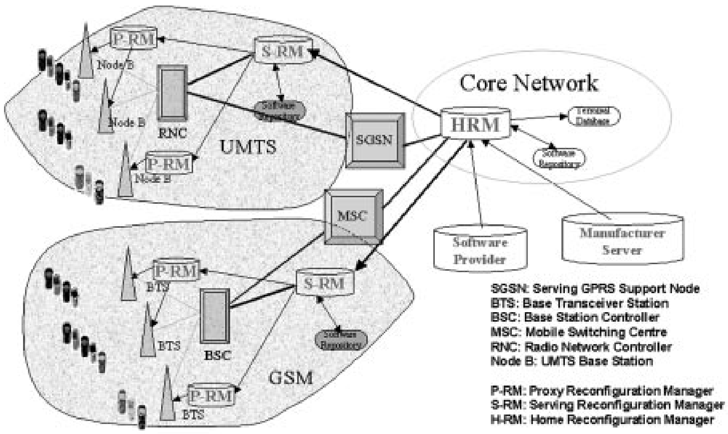

Figure 7.8 Network-centric architecture

Details of the proposed system architecture are depicted in Figure 7.9. The main modules and their associated functionalities are:

- mode negotiation and switching module: leads the reconfiguration process, negotiation and decision in tight cooperation with other modules;
- configuration management module: manages the cohabitation of multiple hardware and software versions within the terminal;
- reconfiguration management module: manages the terminal reconfiguration, taking into account the terminal capabilities and resources;
- mode identification and monitoring module: discovers, identifies, and monitors existing alternative modes;
- software download module: handles all aspects of software downloading, forming the most appropriate download strategy;
- authentication module: performs the authentication before any service negotiation.

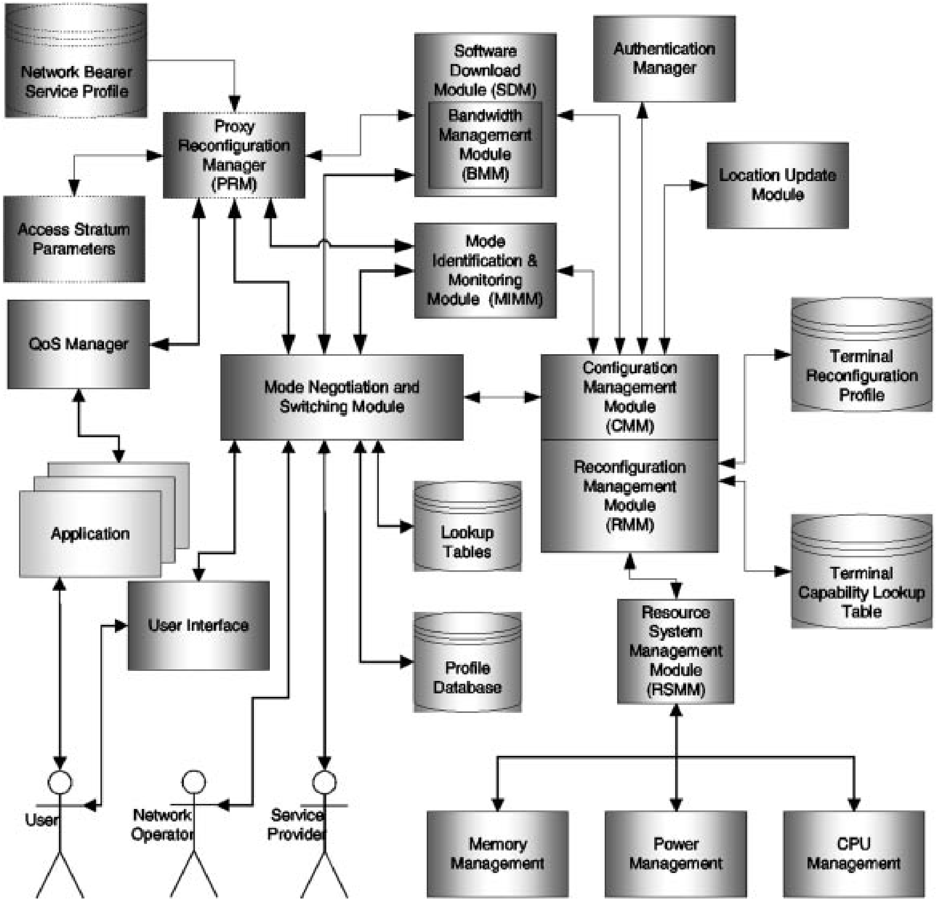

Figure 7.9 System architecture

Some other important entities and components are:

- network bearer service profile: contains information about the currently available services and their customization parameters (e.g. QoS parameters);
- proxy reconfiguration manager: interacts with network entities so as to minimize the traffic over the wireless link;
- user, operator, service provider: actors who may trigger a reconfiguration process;
- application: is an active part during reconfiguration process and may impose several requirements regarding radio access technology to be finally chosen.

This system architecture definition is still under analysis, the distribution of functionalities across modules and the detailed interactions between modules continue to be investigated.

7.4.2.5 Security Issues for Reconfigurable Terminals

There are a large number of security issues related to reconfigurable terminals. This section is focused on two specific issues, namely, software integrity and controllability of the terminal.

Software Integrity

For the reconfiguration of a terminal, software modules may be required that are not already available on the terminal. To enable the reconfiguration, missing modules have to be loaded. For secure download one approach is the use of trustworthy software providers that can be relied upon to provide only well-behaving software. Before a terminal accepts a software module it has to perform security checks that ensure that the loaded software module originates from a trusted provider and that it has not been tampered with.

MExE[10] [24] provides a framework for secure software download and installation that is independent of the means of software provisioning and makes use of well-established technologies from the Internet world. Java sandboxes and digital signatures based on public-key cryptography are used to restrict the permissions of software downloaded to the terminal. MExE defines three different security domains on the terminal, associated respectively with the manufacturer, operator, and trusted third party. A root public key controls access to a security domain. An untrusted domain is also defined to allow untrusted applications to run in a secure sandbox.

The awareness that it may not be possible to use a public-key-based solution on low-end devices has led to the proposal of an alternative that involves a ‘security box’ in the security checks. The requirements on the terminal capabilities are reduced as no public-key cryptography is used. Figure 7.10 illustrates this approach.

The software server is an untrusted repository that provides software modules for download. In particular it can be another terminal. The security box contains the checksums of all valid software modules. For the computation of the checksum of a software module, the security box and the mobile terminal share a secret key. After the download of a software package, its checksum is computed and compared with the value stored in the security box. If both are equal, the loaded software is installed.

To assess this proposed solution it must be analyzed and compared with an approach based

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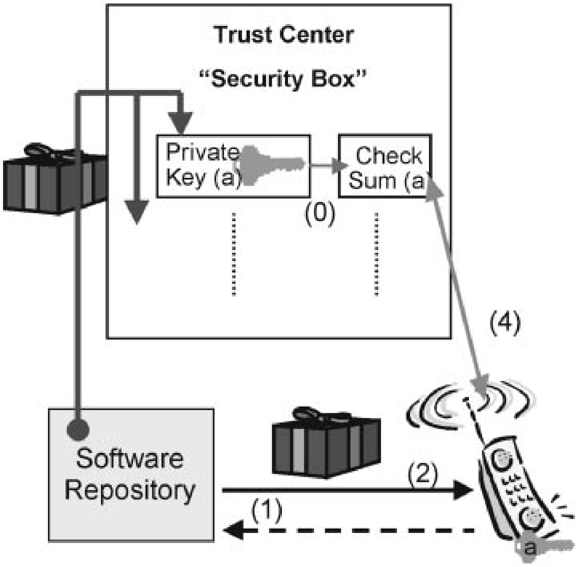
[10] A comprehensive description of the MExE architecture, standard, and capabilities is given in Chapter 9.



(0) Generation of checksums with personal/terminal specific keys

(1) Request of SW package

(2) Download of SW package

(3) Generation of SW checksum with personal/terminal specific key (a)

(4) Transfer of checksum and comparison with stored (or ad-hoc calculated). If successful comparison installation of SW package

Figure 7.10 Secure software download using a 'security box'

on digital signatures. In particular, the prerequisites and assumptions, required infrastructure, scalability, overhead and performance issues must be investigated. This investigation is underway within TRUST.

Terminal Controllability

Despite the fact that many tests can be performed to ensure that the software works correctly, there is always a possibility that a bug or malicious software will survive the tests and cause malfunctions to the terminal. Thus, it is essential to dedicate a non-reconfigurable part (modules) within the software of the SDR terminal. This part (modules) will contain all the software that is responsible for the most sensitive functions of an SDR terminal, such as functions related to the radio interface or any other function that can affect the performance and integrity of the network. This software will not be reconfigurable, thus providing a safe, reference point in the case of a serious software breakdown. The 'secure software' part (modules) may be able to be controlled by parameters, which in turn must be completely safe and subject to the strictest security measures.

Part of this secure, non-reconfigurable software should be (Figure 7.11):

- the software which controls functions that allow connectivity and monitoring of the network;
- software responsible for the corrective actions, which will be necessary in the case of a major software malfunction; and
- other ‘safe’ functions software.

The exact software and functions that should be included in this secure software scheme may be a subject for minimized standardization and/or type approval (to be further studied and elaborated).

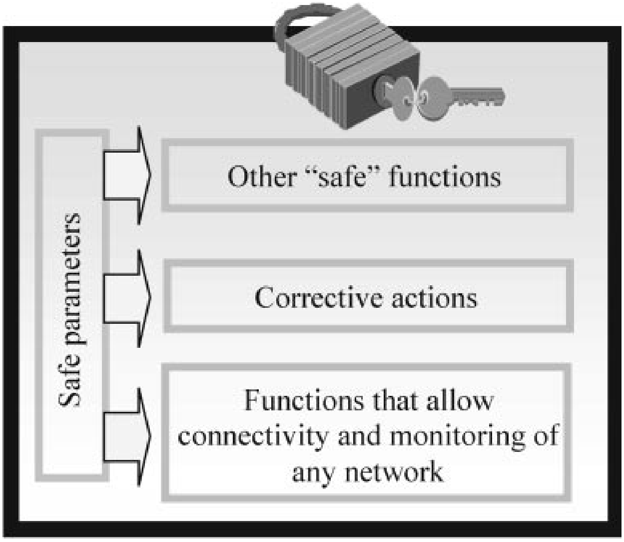


Figure 7.11 The secure software

7.4.3 Expected Results and Timeframes

The main expected results for the above research topics, within the framework of the reconfigurable terminal beyond 3G, are the following:

- achievement of a shared and realistic SDR vision from user, operator, and regulator point of views;
- definition of the potential system architecture supporting terminal reconfiguration;
- definition of networks protocols and procedures for terminal reconfiguration in hierarchical and decentralized networks;
- progress in research on enabling technologies and definition of solutions for the main bottlenecks;
- validation of concepts and demonstration of services.

An evolution path for future developments has been identified (Figure 7.12) which addresses terminals, networks, and regulation issues.

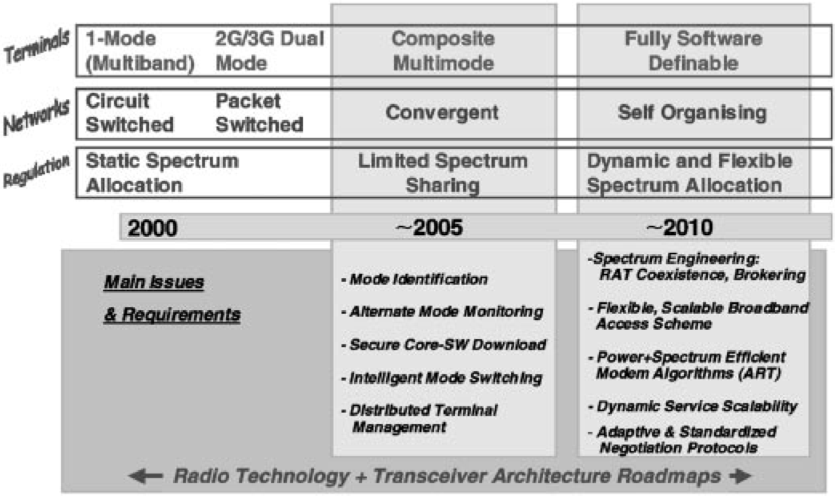


Figure 7.12. Potential timeframe for reconfigurable equipment

This timeline presents the medium term requirement for reconfigurable terminals to address optimum service delivery and synergy in a composite radio environment, and the longer term view of dynamic spectrum access in a scalable communications environment.

7.5 Summary

In this chapter we have sought to provide a comprehensive overview of the background and status of software radio within Europe. The origins and drivers in Europe have been different from elsewhere, reflecting the region's early transition from analog to digital mobile telephony; in Europe, the imminent introduction of 3G has emerged as a key stimulus for SDR research since the late 1990s.

The international collaborative research framework encouraged and financially supported by the European Commission has served as a major stimulus within Europe. The proactive role of the Commission in identifying the potential importance of SDR and in widening the early debate to develop the concepts of 'reconfigurable radio' has been of particular significance. Industry has responded, with a range of early and current research projects described. The interaction of these projects, under the auspices of the reconfigurability cluster, continues to play a major role in the development of shared views amongst different companies. Finally, a brief overview has been provided of the future research required and the anticipated outcomes and time scales for implementation.

Acknowledgements

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Software Radio in Japan

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Software radio has emerged, by virtue of its very potential, as a group of technologies of global interest. Given Japan's major role in recent years in the development of mobile technology – *i*-mode and 3G (FOMA) – it is thus only natural that Japan has also played an early and active part in the development of concepts and technologies for software radio. This chapter provides an overview of these activities, describing the role of the players on the Japanese national scene, as well as summarizing the technical contributions of some of the major companies and organizations.

8.1 Research Cooperation between Industry, Government, and Academia

The third generation (3G) of mobile communication systems, i.e. IMT-2000, is scheduled to begin service in Japan in October 2001 aiming for higher quality and variable transmission speed for multimedia information. Thus research interest has now moved beyond 3G, to explore topics such as MMAC in Japan, U-NII in US, and BRAN in Europe.

Today, and in the future, various systems coexist with different standards in the fields of mobile communications and wireless local area network (LAN). In the transition between 2G and 3G mobile cellular systems, there exist many different standards such as PDC, GSM, IS-95, PHS, DECT, EDGE, GPRS, IMT-2000, cdma2000, etc. However, their interoperability has not yet completely been ensured between handset and base station. Although IMT-2000 was conceived as enabling a single global standard, differences still remain.

In wireless LANs, there are such standards as IEEE802.11b (ARIB-STD33), IEEE802.11a (ARIB STD-T71), and HBRAN (ARIB STD-T70), but various wireless LANs using DS, FH, OFDM, etc. coexist, including some 'de facto' standards, such as Bluetooth. Their different specifications result in a lack of interoperability among them.

Japanese customers are used to mobile wireless access to the Internet with a handset such as *i*-mode of NTT DoCoMo and to wireless connections in intelligent transport systems (ITS) such as global positioning systems (GPS) car navigation, dedicated short range communications (DSRC) including electric toll collection (ETC) and inter-vehicle communications

(IVC). To satisfy such demands, many manufacturers in Japan have been developing various wireless systems with different specifications. However, radio frequency resource is limited in practice, co-located systems tend to interfere with each other, and sometimes too much wireless equipment needs to be installed in a vehicle. This, in Japan, is another urgent driver for a software defined radio (SDR) system with multimode and multifunctional capability.

In order to respond to such needs, the IEICE Software Radio Technical Group (SR-TG) was formed in December 1998 in Japan in order to promote research and development in the field of software defined or reconfigurable radio systems. The purpose of the IEICE SR-TG is as follows:

1. Promote research and development in a field of software defined/reconfigurable radio.
2. Allow protocol, software, and hardware to be easily integrated along future digital radio systems, etc.
3. Foster cross-organization and collaboration among academia, industries, and governments.
4. Organize national and international symposia and workshops on SDR.

The IEICE SR-TG covers the following subjects, amongst others:

- theory of software radio
- software and hardware technology for use in software radio
- applications to communications, broadcasting, ITS, etc.
- research into application programming interfaces (APIs)
- standardization of software radio
- information exchange and cooperation with active organizations in other countries

The SR-TG has held technical conferences/workshops three times a year and panel sessions in IEICE annual symposia and at IEEE sponsored international conferences, e.g. PIMRC'99, VTC2000-spring in Japan, over the past 3 years,[1] and occasionally also in conjunction with the SDR Forum.[2] The IEICE SR-TG published a special issue on SDR in the English volume of the *IEICE Transactions on Communications* in June 2000 and a special issue in the Japanese volume of *IEICE Transactions on Communications* in July 2001. A summary of IEICE SR-TG activities during the period from 1999 to the present is listed below.

8.1.1 1999

- January 27: First technical committee meeting (Tokyo)
- March 11: 1st technical conference: Workshop (Yokusuka Research Park: YRP) together with the SDR Forum (March 9–11)
- June 30: 2nd technical conference (Osaka)
- September: Panel session was held in the PIMRC'99 conference (10th International Symposium on Personal, Indoor and Mobile Radio Communications) (Osaka)
- November 17: 3rd technical conference (Nagoya)

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[1] See http://www.ieice.or.jp/cs/sr/jpn/index-e.html

[2] See Chapter 3, which includes information on the development of the SDR Forum's links with the IEICE.

8.1.2 2000

- April 11–13: SDR Workshop (Seoul, Korea)
- April 17: 4th technical conference: Workshop (Yokosuka Research Park: YRP) together with the SDR Forum
- May 16: Panel session at VTC spring (Vehicular Technology Conference) 2000 (Meridian Pacific Hotel, Shinagawa, Tokyo)
- June: Publication of the special issue on SDR in *IEICE Transactions on Communications* (English volume)
- July 21: 5th technical conference (Keio University, Yokohama)
- September 13–15: Tyrrhenian Workshop on SDR (Italy)
- September 30: Panel session in IEICE Annual Conference (Nagoya Institute of Technology, Nagoya)
- October 20: 6th technical conference and Technical Exhibition (NTT, Musashino, Tokyo)

8.1.3 2001 and Beyond

- February 6: Publication of Two Years' Activities Report of SR-TG IEICE in Communication Society Steering Committee Meeting
- March 26–29: (1) Panel session on Applications of SDR; (2) Symposium on Latest Technologies of SDR in IEICE Annual Conference (Ritsumeikan University, Kusatsu)
- April 26: 7th technical conference: Workshop (IEICE Headquarters, Kikaishiko-Kanikan, Tokyo) together with the SDR Forum (April 24–26)
- July: Publication of the special issue on SDR in *IEICE Transactions on Communications* (Japanese volume)
- September: 8th technical conference (Nagoya)
- September 18–21: (1) Panel session on SDR; (2) Technical session on Latest Technologies of SDR in IEICE Joint Societies Conference (University of Electro-Communications, Tokyo)
- December: 9th technical conference (Osaka)
- March 2002: 10th technical conference (Tokyo)

8.2 Research Trends

Software defined radio is a broad concept encompassing all-digital transceivers and software-based adaptability for multi-purposes and multi-applications in multi-environments. A SDR transceiver is generally defined as a transmitter and a receiver implemented by SDR techniques which can adaptively process and control radio frequency (RF) analog hardware with software in digital circuits. It should be a multi-purpose transceiver which is applicable to all, or multiple, purposes and should be an adaptive transceiver which can learn and adapt to all, or a wide variety of, transmission and channel environments with software. Such a concept of SDR is attractive but its implementation is not easy because there are still many problems that need to be overcome. Moreover, SDR is an enabling technology for designing and implementing devices that are capable of downloading or programming their hardware architecture and functionality remotely.

IEICE SR-TG has been covering various subjects in the field of SDR such as architectures, devices, algorithms, description languages, and API, for achieving reconfigurability and downloadability in a SDR [1–3]. Research and development on SDR in Japan tends to focus on wireless hardware, rather than software architecture; this is because most of the researchers in SDR originate from wireless, electrical, or electronics engineering.

A wireless communication system typically consists of several hardware modules such as an antenna, a multiband RF converter, IF band filter, an analog-to-digital converter (ADC), a digital-to-analog converter (DAC), a baseband processor, e.g. digital signal processor (DSP), field programmable gate array (FPGA), application-specific integrated circuit (ASIC), and so on. In order to improve feasibility of a SDR system, such a structure still has several problems. Several major themes which have been discussed at IEICE TG-SR technical conferences and related workshops are detailed in the sections below.

8.2.1 Baseband Processing

To achieve reconfigurability and programmability for broadband signals, high-speed signal processing is required. Even using today’s high-speed DSP devices, it is difficult to do real-time processing of broadband signals. On the other hand, if an FPGA is employed with hardware description language (HDL), real-time processing is more-or-less achievable. Since FPGA devices are designed to be programmable, however, this approach results in a circuit the size of which is several times larger than necessary non-programmable ASICs. To solve these problems, optimum combinations of DSPs and FPGAs – multiprocessor structures – have been researched and presented in IEICE conferences.

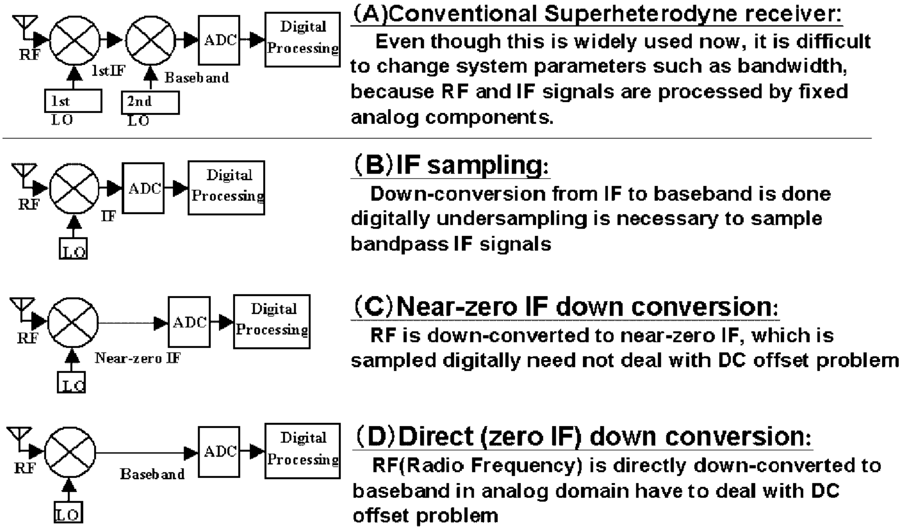
8.2.2 ADC and DAC

Power consumption of ADCs and baseband circuits is a major problem in a battery-powered mobile terminal. Faster ADCs lead to an increase in power consumption, while increasing sophistication of the digital circuitry causes the same problem. To reduce the sampling rate of the ADC, quadrature sampling can be employed. This approach can reduce the rate, and hence power consumption, by using two ADCs for I and Q channels. Band pass sampling for limited-band IF signals has also been presented. A contrasting approach, an architecture of an extremely fast sampling ADC, has also been invented, employing superconductive devices, and its feasibility proven.

8.2.3 Direct Converters

Conventional wireless communication systems typically utilize a double super-heterodyne architecture consisting of RF, IF, and baseband modules, as shown in the first example in Figure 8.1A. However, the nonlinearity and the bandwidth limitation of IF modules limit the flexibility of a SDR system. By omitting IF modules, not only better flexibility but also smaller power consumption and hardware size can be realised. Thus, to avoid the need for IF modules as shown in Figure 8.1B various types of direct converters (DCs) have been proposed, as shown in Figure 8.1C, D.

Direct converters can directly convert RF signals down to baseband or to a very low frequency intermediate frequency signal. Most types of DCs use complex mixers to output IQ baseband signals, whilst a multi-port junction type of DC produced by Sony can reduce power consumption for wider band signals (see Section 8.3.3).



(A)Conventional Superheterodyne receiver:
Even though this is widely used now, it is difficult to change system parameters such as bandwidth, because RF and IF signals are processed by fixed analog components.

(B)IF sampling:
Down-conversion from IF to baseband is done digitally undersampling is necessary to sample bandpass IF signals

(C)Near-zero IF down conversion:
RF is down-converted to near-zero IF, which is sampled digitally need not deal with DC offset problem

(D)Direct (zero IF) down conversion:
RF(Radio Frequency) is directly down-converted to baseband in analog domain have to deal with DC offset problem

Figure 8.1 Receiver architectures

8.2.4 Smart Antennas

In order to create a single hardware system capable of supporting multiple standards, the antenna and RF circuitry must perform flexible broadband signal processing. However, it is typically difficult to implement such a broadband antenna and RF circuitry in an easily controllable manner because they heavily depend on hardware structures that usually have narrowband frequency performance. On the other hand, a baseband circuit is more flexible even though it requires high bit resolution and processing speed in order to make it flexible. Therefore to improve the flexibility and hardware dependency of the antenna, adaptive array antenna or smart antenna techniques must be used to realize a flexible SDR system.

Novel structures and algorithms for an adaptive array antenna with software control, that is a software antenna, have been proposed by Japanese academia and industry [4,5]. As examples of a smart antenna, there are the digital beam former (DBF) and the analog array antenna approaches. With a DBF, it is possible to control the spatial and temporal characteristics of reception by adaptively changing the software algorithms running on parallel signal processing hardware [6]. This is suitable for software radio, where multimode and multiband capability are required.

8.2.5 Automatic Recognition of Modulation Schemes

Using software radio technology, it becomes possible to handle different symbol rates and/or different modulation schemes. When a software radio receiver receives a radio wave of changeable symbol rate or modulation scheme, it will need to recognize them correctly. Reference [7] provides an example of how such automatic modulation recognition may be implemented.

In Ref. [7], the symbol rate of the incoming signal is estimated, by performing a discrete Fourier transform on the received signal. A low-pass filter is then designed, based on the estimated symbol rate, and the received signal passes through the low-pass filter. The time of zero-crossing of signals in the constellation is then measured. The modulation scheme of binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), or 8PSK is then estimated by performing a statistical analysis of relative phase difference.

An alternative approach is described in Ref. [8], where the authors propose recognition of modulation schemes by various analysis of frequency, phase, amplitude, and I-Q patterns. In Refs. [9,10], recognition of phase shift keying (PSK) and quadrature amplitude modulation (QAM) is extended to encompass frequency shift keying (FSK), minimum shift keying (MSK), Gaussian filtered minimum shift keying (GMSK), amplitude modulation (AM), and frequency modulation (FM) by performing an analysis of phase difference histograms between adjacent symbols, symbol radius, and envelopes.

8.2.6 Superconductor Technology

Research into the construction of RF analog filters using superconductor devices is being conducted [11]. A superconducting RF analog filter is proposed which can largely tune the resonant frequency of the resonator by utilizing the fact that the filter is made using thin film technology. The tunable characteristics are obtained by mechanically controlling the distance separating dielectric or magnetic material placed near the superconducting resonator. The resonant frequency, of about 450 MHz, may also be adjusted by applying electric or magnetic fields.

Further research is being conducted into performing digital processing using superconductor devices [12]. By using a single flux quantum (SFQ) device, it is possible to perform digital operations by assigning 0s and 1s to magnetic flux. Simulation results have been obtained showing 100 MHz 16-bit analog-to-digital conversion, which is superior to current semiconductor ADCs.

8.2.7 Other Topics

Software defined radio in Japan stimulates much related research such as adaptive coding/decoding and adaptive modulation/demodulation, in which channel coding and modulation schemes can be adaptively changed to optimize quality of service in transmission according to the prevailing channel conditions and the required services. In particular, various schemes of identifying modulation and coding schemes used by the transmitter have been presented. Download methods have been proposed to ensure security and authentication of downloaded information. Hardware/software co-design is also an important subject in which a system description language should be designed so as to code with a high-level language prior to the hardware/software partitioning stage.

8.3 Software Radio Prototypes in Japan

In order to prove the feasibility of SDR, several organizations have developed prototype software radios as the first step in SDR application studies in Japan. The targets of those studies are to verify the feasibility of SDR functions.

8.3.1 The ARIB Software Receiver

A study group concerned with the development of a software receiver was established within the Association of Radio Industries and Businesses (ARIB) [13,14]. In the period from 1996 to 1998 this study group investigated not only the successful development of terminals commonly used in various systems, but also radio monitoring equipment required to cope with an increasingly complex radio wave environment. As one of the application examples, a prototype software receiver was manufactured and evaluated.

The specifications for the functional model were discussed and the prototype was manufactured as a typical example to allow evaluation of the software receiver. Table 8.1 and Figure 8.2 show the major parameters and the block diagram respectively of ARIB's software radio prototype.

Table 8.1 Parameters of the ARIB SDR receiver

Frequency band	27 MHz, 900 MHz, 2 GHz
Antenna array	6-element circular array
Modulation method	BPSK (binary phase shift keying), QPSK (quadrature phase shift keying), $\pi/4$-QPSK, GMSK (Gaussian filtered minimum shift keying), FM (frequency modulation), AM (amplitude modulation)
Bit rate	8, 16, 32 kbit/s
Direction of arrival estimation algorithm	MUSIC (multiple signal classification)
Interference wave suppression algorithm	DCMP (directionally constrained minimization of power)

Among the applications of the software receiver, radio monitoring in particular requires many functions including direction of arrival estimation, interference wave suppression, and radio wave characteristic measurement. For this reason, its specifications were defined, giving main consideration to this radio monitoring application. The functions that the prototype successfully offers are as follows:

- multimode, multi-rate demodulation
- direction of arrival estimation
- interference wave suppression
- radio wave characteristic measurement
- software download

8.3.2 CRL Parameter-controlled SDR

Communications Research Laboratory (CRL) of Ministry of Posts and Telecommunications (MPT) has proposed a configuration method for a SDR system in order to overcome problems in the full-download-type of SDR [15].

In the proposed method, basic telecommunication component blocks have already been

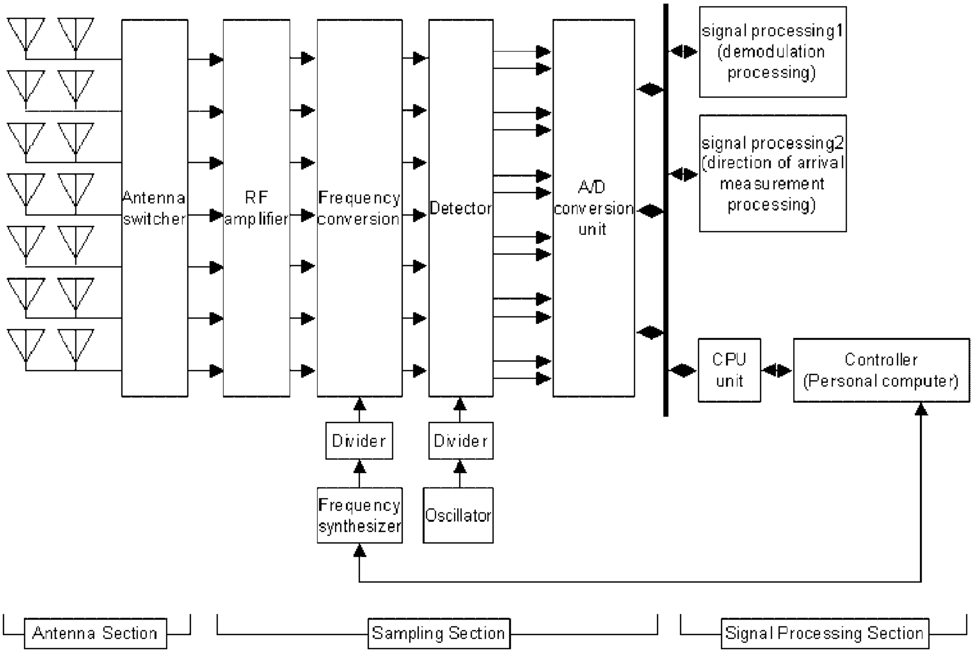


Figure 8.2 Architecture of the ARIB software receiver

implemented in the digital signal processing hardware such as DSP and/or FPGA. For each functional block, the specification is not fixed but is programmable and changeable easily by downloading external parameters. For example, the download parameter for a filter block is only the filter coefficient, and for a coding block the download is carried out with only a parameter for the equation of the generator polynomial. Only by changing the external parameters required, telecommunication systems can be reconfigured. It is called parameter-controlled-type SDR system.[3]

In order to show the effectiveness of the proposed SDR system, an experimental prototype was developed and its transmission performance was evaluated. The system parameters are summarized in Table 8.2.

The experimental prototype can realize three telecommunication systems: PHS (personal handy-phone systems), GPS (global positioning systems), and ETC (electric toll collection) as its Service mode. Moreover, as User mode, it is possible for the user to freely choose between several modulation schemes of GMSK, $\pi/4$-QPSK, BPSK, and QPSK. For PHS and GPS, the antennas of both systems are integrated into a single antenna; this is possible because the frequency utilized in GPS (1.5 GHz band) is quite close to that of PHS (1.9 GHz band). The external parameters, used to configure the system, are supplied from a notebook type computer connected to the experimental prototype using a 10Base-T Ethernet cable.

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[3] The exploration of such concepts in Europe is described by F. Jondral in his chapter in the companion volume to this, *Software Radio: Enabling Technologies*, Tuttlebee, W. (Ed.), Wiley, Chichester.

Table 8.2 Major parameters of the CRL experimental prototype

Services	(Service mode)	Frequency	PHS – 1.9 GHz
	PHS, ETC, GPS		ETC – 5.8 GHz
	(User mode)		GPS – 1.5 GHz
	BPSK, QPSK, π/4-QPSK, GMSK		User mode – IF band
Modulation	PHS – π/4-DQPSK	Data rate	PHS – 384 kbps (carrier bit rate)
	ETS – ASK		ETC – 1024 kbps:2048 kband (data rate)
	GPS – BPSK + Spread Spectrum		User mode BPSK, QPSK, π/4-QPSK – 384 kbps (carrier bit rate)
	User mode – BPSK, QPSK, π/4-QPSK, GMSK		GMSK – 270.833 kbps (carrier bit rate)

8.3.3 Sony CSL – SOPRANO

The Advanced Telecommunication Laboratory (ATL) of Sony CSL has proposed a SDR platform called SOPRANO (software programmable and hardware reconfigurable architecture for network) [16]. It is capable of handling multiband and multimode radio standards for such applications as wireless LAN and cellular phone systems, whose carrier frequency ranges from 800 MHz to 5 GHz. The proposed platform consists of a reconfigurable digital circuit, ADCs, DACs, and a novel low-power wideband analog component called a 'multiport junction MMIC' which can directly convert RF carrier signals to baseband. The configuration of SOPRANO is shown in Figure 8.3 and its parameters are shown in Table 8.3. The

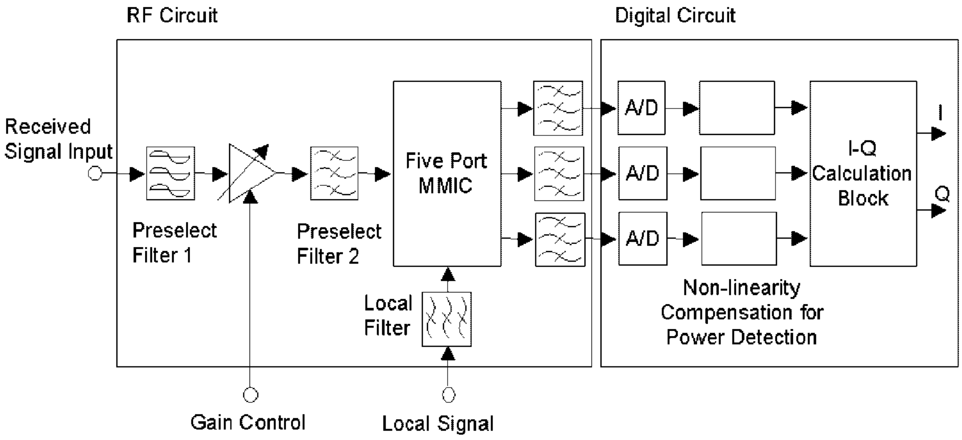

Figure 8.3 The SOPRANO testbed architecture

Table 8.3 Features and capabilities of SOPRANO

Bands (available frequency)	2.45 GHz, 5.25 GHz (500 MHz–9 GHz)
Modulation	BPSK, QPSK, 8PSK, 16QAM, and 64QAM
Bandwidth	15 MHz
Hardware features	Direct conversion based on 5-port junction MMIC (zero IF)
Software features	Design flow from C++ to NETLIST
Modulation identification	Automatic identification of modulation scheme among BPSK, QPSK, 8PSK, 16QAM, and 64QAM

system prototype was made in October 2000 and its capability was demonstrated. Its flexible digital hardware and analog RF components were capable of handling multiband and multimode radio signals. The project is ongoing and the performance of the multi-port junction MMIC is being improved.

The digital platform can accommodate various wireless schemes by reconfiguring the hardware. A new design methodology accepts hardware description in the C language; the hardware architecture is synthesized by optimizing its hardware resource and scheduling. The C program is translated to hardware description language (HDL) which is then converted to a network of electronic components by a synthesis tool. The network is then mapped to an FPGA.

The receiver MMIC is based on the linear operation of the device, and related non-linear effects may be ignored – the power level of the local oscillator is much lower than in the classical approach. Moreover, the proposed direct conversion receiver is able to support a wide bandwidth that is more demanding for conventional I/Q receivers. The received signal passes through pre-select filter circuits, and the gain controlled LNA, and is then fed to the 'five port junction MMIC'. The output of the MMIC is A/D converted and fed to the digital signal processing part. In this part, the non-linearity is compensated and the in-phase (I) and the quadrature (Q) values of the signal are calculated from the three output voltages of the MMIC.

8.3.4 NTT – Cellular Base Station and Terminal

NTT has developed a SDR prototype base station and personal station for various types of cellular systems [17]. Major parameters and a block diagram of NTT's SDR prototype system are shown in Table 8.4 and Figure 8.4.

The prototype system is composed of RF/IF circuits, ADCs and DACs, pre-/post-processors, a CPU, an I/F (interface) circuit, and DSP parts. The CPU, DSPs, and an interface circuit are interconnected by a 32-bit VME-bus. The base station offers an ISDN interface, while the personal stations have voice and bearer communication interfaces. The pre-/post-processors, which handle multiple access and waveform shaping, are employed to reduce the main DSP loading.

When in receive mode, the 39 ± 6.5 MHz IF signal is A/D converted using 12-bit quantization with 52 MHz resolution. The pre-processor under-samples the IF signal, and a channel signal is digitally down-converted, filtered, and fed to the DSPs. In transmit, the reshaped and channel-multiplexed baseband signal is up-sampled with a 10-bit resolution D/A converter using 10-bit quantization at 104 MHz. The signal is zero-stuffed before D/A conversion to improve the aperture effect due to the imperfection of the pulses.

Table 8.4 Key features of the NTT SDR prototype

RF band	2.45 GHz
Bandwidth	13 MHz
Freq. conv. method	Double super-heterodyne
IF	215/39 MHz
No. of RF/IF systems	3
Duplex scheme	Time division duplex (TDD)
External interface	ISDN (base station) Voice, bearer (personal station)
DSP performance	6400 MIPS
AD conversion	IF under-sampling

The implementation uses four commercially available 1600 MIPS DSPs (offering 6400 MIPS) mounted on a single board. The processing load required for transmission is relatively low compared with that needed for the receiving function. Thus, basically one DSP is assigned to the transmission side and three DSPs to the receiving side. Task programs performing modulation and demodulation, CODEC, and adaptive array control are loaded onto the DSPs. Those programs communicate with the program on the CPU through the macro interface. The CPU handles communication control and system management. The developed prototype can operate in PHS mode or/and lower bit rate mode comparable to the cellular system.

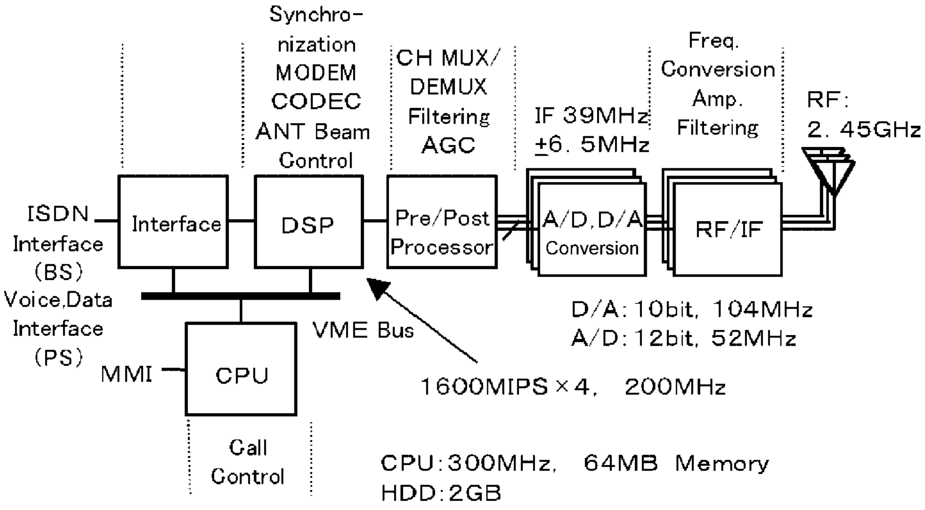

Figure 8.4 Block diagram of the NTT SDR prototype

8.3.5 Toshiba – Handheld Direct Conversion Receiver

Toshiba has investigated the broadband and flexible receiver for the handheld SDR [18]. The proposed SDR architecture is based on the direct conversion and low intermediate frequency (low-IF) principle with digital channel filtering, which provides the receiver with flexibility for the multistandard application. This architecture also enables A/D converter activating essentially in baseband or low frequency so that the clock jitter, which is an important subject in the well-known IF-sampling method, can be reduced. Basic performance of the proposed architecture has been confirmed by implementing an experimental prototype. Basic performance of the proposed SDR prototype using the direct conversion approach has been experimentally confirmed. The hardware specifications are shown in Table 8.5.

Table 8.5 Hardware specifications of the Toshiba direct conversion receiver

Antenna	Tx	$\lambda/2$ Dipole
	Rx	Microstrip
LPF (anti-alias and system selection)	Type	4th order Chebyshev (cascade of 2nd order multiple feedback and 2nd order Sallen–Key)
	Cutoff frequency	1 MHz
ADC	Sampling rate	5 MHz
	Resolution	14 bits
FIR filter (channel selection)	Cutoff frequency (including decimation filter)	96.5 kHz (for CH1)
		137.5 kHz (for CH2)
	Tap number	121

8.3.6 NEC – Environmentally Adaptive Receiver

NEC and Anritsu have developed and evaluated the software receiver that could accommodate future needs [19]. As a first step to make the receiver useful, the modulation mode classification algorithms were studied; as the next step, an adaptive receiver that is an evolution type of software receiver has been developed, i.e. a receiver which can automatically adapt to its radio environment.

The adaptive receiver analyzes the incoming unknown communication signal and automatically extracts information on the signal parameters, allowing automatic demodulation of the received signal. A modulation identification algorithm using the analysis techniques of envelope analysis, symbol radius distribution characteristic analysis, and phase difference histogram analysis (between adjacent symbols) were proposed and the experimental results reported. The major parameters of the prototype receiver are shown in Table 8.6.

8.3.7 Hitachi Kokusai Electric – Digital and Analog Prototype

Hitachi Kokusai Electric has developed a prototype which provides compatibility with the typical types of waveform for both digital and analog modulation as well as full duplex for the

Table 8.6 Major parameters for NEC/Anritsu's prototype SDR receiver

Demodulation modes	Analog – AM, FM Digital – FSK, MSK, GMSK, BPSK, QPSK, π/4shift-QPSK, 8PSK, 16QAM
Access type	TDMA, SCPC
Symbol rate	10 Msymbol/s max.
Speech codec	32 kbit/s ADPCM, CVSD-DM
Communication protocol	RCR-STD-28 (PHS)
Sampling method	IF sampling (under-sampling)
IF input	100 MHz max.
Software download	Via the LAN

study of the technical issues such as digital signal processing, RF signal processing, software download, and software adaptability [20]. The under (band pass) sampling scheme was employed for the receiver of the prototype. As a result of evaluation tests, it was recognized that the developed prototype presents better characteristics than that of the conventional radio equipment for each type of waveform in both digital and analog modulation. The major parameters are shown in Table 8.7.

Table 8.7 Major parameters of the Hitachi Kokusai SDR prototype

Frequency	455 kHz–100 MHz
Modulation	FSK, BPSK, QPSK, 16QAM, AM, FM, SSB
Information bit rate	50 bps–64 kbps
Access	Simplex/two way
Digital signal processing	3200 MIPS/module
Conversion (max.)	200 k/64 Msps
Conversion quantization	16/12 bits
Conversion (max.)	30 M/125 Msps
Conversion quantization	16/14 bits
Common bus	VME-bus

8.3.8 Toyo Communication Equipment and Tohoku Electric Power – Radio Base Station

Toyo Communication Equipment and Tohoku Electric Power Co. have developed the software radio prototype for the radio base station [21]. A design method of SDR including RF section has been proposed and its usefulness by the experiment has been confirmed. It can handle π/4-QPSK and FM modulated signals. The major parameters are shown in Table 8.8.

8.4 Conclusions

Japan has been active in software radio since the late 1990s, is today actively engaged with the wider global SDR community, and has already fielded some important and

Table 8.8 Major parameters of Toyo/Tohoku Electric's prototype SDR base station

RF frequency	370–380 MHz
RF gain (Rx)	15–14 dB
RF noise figure (Rx)	6.5 dB
Tx IF frequency	10–20 MHz (BW 10 MHz)
Rx IF frequency	65–75 MHz (BW 10 MHz)
A/D, D/A conversion rate	40 MHz (max.)
A/D, D/A conversion	12 bits
DSP processing speed	320 MFLOPS/DSP
Simultaneous Tx/Rx channels	4 channel
Tx channel bandwidth	1.25 MHz (max.)
Rx channel bandwidth	650 kHz (max.)
Modulation/demodulation	$4/\pi$-QPSK, FM
Option	Spectrum, BER display

innovative contributions. The focus of software radio research and development in Japan is primarily in the hardware arena. This chapter has described the key technical challenges that Japanese companies and academia have chosen to address and approaches which have been adopted. The contributions of the key players and the practical testbed implementations which have been fielded to verify the theoretical ideas proposed have been described.

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9

First Steps to Software Defined Radio Standards: MExE, the Mobile Execution Environment

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The role of open standards in wireless telecommunications cannot be overstated, allowing as they do interoperability between equipment from a variety of manufacturers, whilst, with well designed standards, still allowing plenty of scope for individual supplier differentiation. With the advent of software defined radio (SDR), the precise nature, extent, and role of standardization is changing. Whilst the full implications of air interface reconfigurability have yet to be appreciated and addressed, first steps in standardization have been taken in the very recent past, with the standardization of the mobile execution environment (MExE), a 3rd Generation Partnership Project (3GPP) standard that provides a standardized execution environment on a mobile terminal. MExE is essentially a security framework to download and execute software on the mobile terminal. It is anticipated that this framework will increasingly be exploited to support SDR capabilities in a standardized manner in future 3G and 2.5G terminals.

MExE terminals will enable operators, manufacturers, and third party applications developers to provide services that can execute directly on the mobile terminal. Such services will not be restricted to telephony-based services, but may include games, multimedia messaging, information, and software upgrade services. MExE terminals are capable of downloading applications and content from a MExE server after a process of capability negotiation. Currently, these applications may either be based on wireless application protocol (WAP) or on Java. These technologies are supported in three different platforms or ‘Classmarks’, one based on WAP and the other two on Java. A MExE device may support any one or more of these Classmarks. MExE is not tied to any particular bearer technology either, although clearly multimedia enhanced applications can benefit from bearers with higher data rates.

The main contribution of MExE towards the underlying execution platform is security. The security framework for the execution environment is based on a public key infrastructure (PKI). Application developers may sign their applications using their public keys to authenticate it to the terminal. An application with a valid digital signature is considered to be trusted. A trusted application can have access to greater functionality on the terminal than an untrusted application. The ability to authenticate downloaded content and then to assign different capabilities using secure domains is a cornerstone to the success of SDR.

9.1 ETSI, 3GPP, the SDR Forum, and MExE

Early work on the MExE standard began under the auspices of the Special Mobile Group 4 (SMG4) within the European Telecommunications Standards Institute (ETSI) in the late 1990s, predating the establishment of the 3GPP activity, with an initial focus limited to downloading new capabilities at the applications layer to mobile phones. As originally conceived MExE was aimed simply at evolving global system for mobile communications (GSM) toward a client/server architecture for advanced mobile data services. However, it was recognized that MExE need not be restricted to GSM networks but had a much wider potential and in fact it is expected to be deployed in a wide variety of networks.

In Europe at that time awareness of software radio was relatively new and the relevance of the activities of the SDR Forum (active mainly in North America still at that time) was not immediately apparent to many. However, the increasing involvement of certain European players in the SDR Forum work, notably Orange, enabled connections to be made, creating a bridge for cross-fertilization and the possibility of extending the scope of the MExE specification beyond its early vision to support a broader SDR capability.

As described in Chapter 3 by Margulies, the early activities of the SDR Forum gave rise to the creation of its Technical Report, version 1.1 of which was released early in 1998. Issues of software download mechanisms and processes were an important early focus of the work of the Forum, documented in Chapter 6 of the Technical Report. With increasing European involvement in the SDR Forum during 1999, the report was revised during the period February through November of that year to take account of the European WAP and MExE developments. In September 1999 a formal liaison was established with 3GPP, which had by then assumed responsibility for MExE, and also with the WAP Forum. Three months later, in December 1999, a proposal relating to the implementation of software download, based upon the Forum’s Technical Report, was submitted by the Forum to 3GPP MExE and to the WAP Forum. The submission was favorably received by 3GPP and a decision was made at the March 2000 MExE meeting to include initial SDR specifications in the MExE Release 2000 specification – the first steps in global standards for SDR.

9.2 MExE Fundamentals

In this section we provide an overview of what the MExE specification covers and comprises, providing a basis of understanding for the detail provided in the subsequent parts of the chapter.

The MExE specification [1] describes three different so-called ‘Classmarks’ which describe the base software technology employed. MExE Classmarks 1 and 2 were defined in Release 98 of the specification, whilst Classmark 3 work was completed in time for inclusion in Release 2000 (or Release 4). The main difference between these Classmarks is the underlying technology used to define the execution environment.

- Classmark 1 is based on WAP specified by the WAP Forum.

- Classmark 2 is based on PersonalJava and the JavaPhone application programming interface (API) from Sun Microsystems.
- Classmark 3 is based on the connected limited device configuration (CLDC) and the mobile information device profile, specified as part of the Java community process (JCP).

As part of MExE Release 5 work, a fourth Classmark is being standardized, built on the common language infrastructure (CLI) from European Computer Manufacturers Association (ECMA). CLI is based on the compact.NET framework from Microsoft. Figure 9.1 illustrates the current MExE specification with respect to different Classmarks.

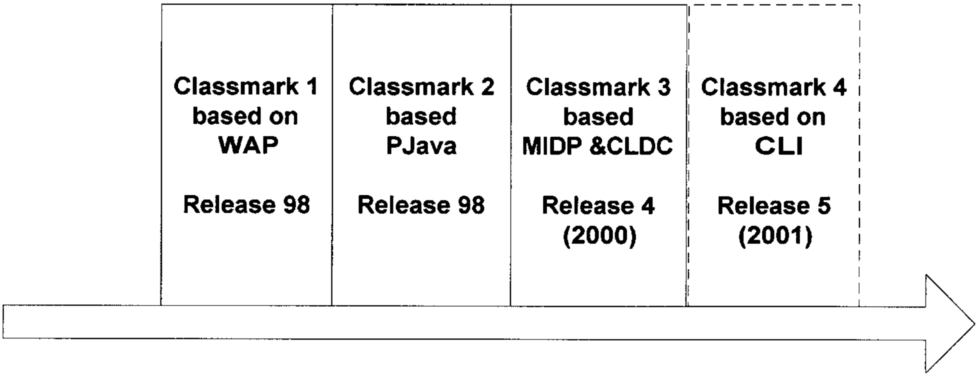

Figure 9.1 MExE Classmarks

9.2.1 General Features

For a device to be deemed MExE compliant, it must support at least one of the Classmarks. In fact the specification allows for devices to support multiple Classmarks, meaning that a Release 4 compliant MExE device could potentially support up to three Classmarks. A multiple Classmark device must conform to all the requirements for each Classmark. However, the commercial usefulness of such a device is questionable, given that similar services would be available across all Classmarks.

9.2.1.1 Capability Negotiation

A typical MExE terminal may thus support one of three different Classmarks; in addition there are optional features in the specification that it could contain. This flexibility could potentially make it difficult for a service environment to know the exact capabilities of the terminal. In order to address this issue, a MExE-capable terminal supports a mechanism to inform the MExE service environment (MSE) of its capabilities. The MSE uses this information to decide what services should be offered to the terminal. All MExE devices must support this capability negotiation mechanism (Figure 9.2). In addition it is possible for the MSE to inform the MExE device of the capabilities of the service environment. This feature is at present not standardized, as the MSE itself is outside the scope of the MExE specification.

Capability negotiation takes place only during the initial setting up of a connection between the terminal and the MSE and, in general, takes place before any content is

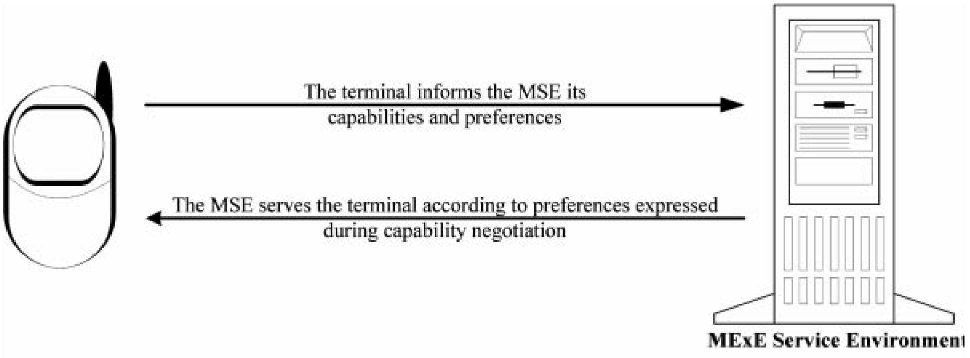

Figure 9.2 MExE capability negotiation

exchanged between the terminal and the MSE. After the initial negotiation, the device can subsequently update the MSE in respect of any changes to its capabilities. For example, the terminal might enter an area with general packet radio services (GPRS) coverage, whilst the original negotiation only informed the MSE of GSM coverage. Or there might be a change in the input devices – for example the device might have gained access to a full size keyboard via a Bluetooth interface since the last capability negotiation was performed.

The MExE device interacts with the MSE using hypertext transfer protocol (HTTP/1.1) [2] or an HTTP/1.1-derived protocol similar to the WAP session protocol (WSP) specified by the WAP Forum. The capabilities themselves are communicated using composite capability/preference profiles (CC/PP) [3], defined by the World Wide Web Consortium (W3C). CC/PP uses the resource description framework (RDF) [4], to encode metadata in XML. However, the actual properties and schema used are based on the WAP user agent profile (UAProf) [5] specification. Essentially UAProf provides an RDF-based schema and vocabulary for CC/PP that includes the class definitions and semantics of attributes described in a user agent profile. In addition, UAProf provides guidelines on how the schema may be extended to support a composite profile to meet future requirements. Together, these mechanisms provide an efficient method of informing the terminal device capabilities to the MSE.

The MExE specification has identified a set of mandatory and optional properties from the UAProf specification that are relevant to a MExE-capable device. Among them are a few MExE-specific properties that have been added to the UAProf specification, such as the attribute 'MexeClassmarks' which is used to inform the MSE of the Classmarks that are supported on the device. Table 9.1 shows some examples of UAProf fields contained within the MExE specification. The specification requires all MExE devices to support the mandatory fields while support for the remainder of the fields is only recommended.

There is no requirement for a MExE device to inform the MSE of all the supported capabilities. Also, the MSE may or may not use the capabilities informed by the device when services are offered. Additionally, there is no requirement for these fields to be sent directly from the device – the MExE device may choose to inform the MSE by directing it to a URL containing the capabilities of the device.

Table 9.1 Some examples of UAProf fields contained within the MExE specification

Attribute	Description
Mandated properties	
MexeClassmarks	List of supported MExE Classmarks
MexeSpec	The first two digits of the MExE specification version that the MExE device conforms to
MexeSecureDomains	Indicates whether the device supports the MExE security domains
Recommended properties	
Vendor	MExE device vendor
Model	MExE device model number
SoftwareNumber	The number of the MExE device specific software
ScreenSize	The size of the MExE device's screen in units of pixels
ScreenSizeChar	Size of the MExE device's screen in units of characters (based on the standard font)
ColorCapable	Whether the MExE device display supports color

9.2.1.2 Content Negotiation

Content within the MSE may take different formats; however, the user terminal device may or may not have support for a given content format. In order to ensure that the MSE uses the desired and the most efficient content format, MExE devices support a mechanism for content negotiation. Content negotiation may be initiated either by the MExE device (client-driven negotiation) or by the server (server-driven negotiation). MExE uses methods specified in HTTP/1.1 or WSP for content negotiation. For example, the server might support a large number of different audio file formats, while the MExE device may only support MP3 – through content negotiation this preference could be informed to the MSE.

9.2.1.3 The User Interface

A MExE device may potentially support hundreds, if not thousands, of different applications and services. Nevertheless, MExE devices will encounter similar problems facing current mobile devices – limited screen sizes, processing power, and battery life. This makes it a challenging task for the device manufacturer to present all these new features and functionality to the user in a simple and usable fashion. However, the complexity of the device must be well concealed from the user – this is vital if MExE is to be adopted by the mass market.

MExE itself does not mandate any features that are associated with the user interface. This decision is left to the creativity of the manufacturer. It is expected that each manufacturer will develop or continue with their own unique signature within the user interface, potentially becoming a key feature differentiating different MExE devices. At the same time manufacturers, operators, and third party service providers will be able to offer customized user interfaces to their customers, an important part of the branding process that many operators have already embarked upon.

9.2.1.4 The User Profile

It would be a daunting task for the user to have to remember and to input his or her preferences every time a service is accessed or an application is launched, particularly difficult since different services may require different terminal settings. Current terminals already support a level of personalization; for example, it is possible to download a picture to be displayed when the terminal is in standby mode or to customize the ring tone. However, at present these features are not standardized and there is no way of informing the network about these preferences such that network services could be tailored according to these local preferences on the terminal.

By bundling user preferences into profiles in a standardized manner MExE provides a foundation for these preferences to be used within the MSE. Further, the standardized nature means that user profiles developed by third parties could be downloaded to the terminal to suit different device usage patterns, to form an integral part of customizing a terminal. In essence the user profile is a standardized way of capturing user preferences, which may be communicated to the MSE, alongside capability and content negotiation. It should be noted that the implementation of the actual preferences themselves within a user profile would ultimately depend on device functionality. A MExE device could potentially support any number of user profiles either on the terminal or on a remote server. If supported on a remote server, the URL could be sent to the MSE during the capability negotiation process. MExE does not mandate the support of user profiles within the specification, nevertheless it is anticipated that the majority of terminals will support one or more user profiles.

These user profile preferences are presented in a standardized format based on the CC/PP from W3C. Preferences that are supported include user interface personalization and service management personalization. Additional MExE preferences could be proposed in the future. The current MExE specification mandates the support for the preference in downloading applications on to the terminal; support for other preferences are only recommended and include preferred languages and acceptance of WAP pushed messages.

9.2.2 Content Downloads

An important feature that differentiates MExE terminals from their conventional counterparts is the ability to download content within a standardized security environment regardless of the underlying execution environment. The downloaded content may be executables or just simple text files. MExE terminals with secure domains have optional support for SDR capabilities; for these terminals the downloaded content could also include terminal core software. This capability was introduced to the specification in August 2000 following a proposal from the SDR Forum in March 2000. The support for SDR capabilities within the current MExE specification is identified in Section 4.14 ‘Core Software Download’. Furthermore, Table 6 ‘Security domains and actions’ was updated to reflect that SDR capabilities are unique to the device manufacturer’s domain.

The download itself may take place over any access network, it need not necessarily be a cellular mobile network; for example, the access network could be a short-range local wireless technology like Bluetooth (IEEE802.15) or a wireless LAN technology (IEEE802.11b).

Download of content onto the device will be subjected to capability and content negotiation, together with preferences expressed through the user profile. In addition all downloaded content will be subjected to the MExE security framework. This means once downloaded, prior to installation, all content will be allocated one of two trust states, i.e. trusted or untrusted. The trusted content will be designated to the appropriate secure domain, depending on the RPK used to verify the certificate chain of the signed package (see Section 4 for more details); SDR content will most likely be dealt with within the manufacturer domain.

The MExE architecture is open and hence the MSE may contain services from the operator, the manufacturer, or from any third party application developer. Depending on the supported Classmark or Classmarks of the terminal, this will give the user access to a wide range of downloadable applications and services, as discussed in Section 5.

9.2.3 Service Provisioning

Service provisioning in general refers to the process of a service being discovered, installed, and subsequently managed. MExE requires that a device must be capable of supporting services either in a WAP (Classmark 1) or a Java (Classmarks 2 and 3) environment. MExE recommends that service discovery be based on a browser environment using either WSP or HTTP, making the user experience similar to that of the Internet. Nevertheless it does not mandate a particular discovery mechanism. There could be two ways of finding out what services are available from the MSE – the MSE could advertise the services via an agreed mechanism, for example based on HTTP, or alternatively the device could have an application that proactively explores the services available from the MSE.

MExE also does not specify a service transfer mechanism. As highlighted earlier, this could occur over any bearer and over any standardized transport mechanism using any supported protocol. A MExE device could also download services from other MExE devices. This means that any local issues on the terminal, for example digital rights management (DRM), have to be addressed separately.

Once a service has been successfully transferred to the terminal, it can be installed and configured according to the user’s preferences. This process may take place automatically, according to the preferences set in the user profile, or else it may be done manually. After the installation process the service may be configured to suit any local requirements, similar to the PC model, for example granting user permission for a particular action. The configuration of a service may also be done at any later time and MExE requires these changes to be applied at the earliest possible time. For example this could involve changing the type of permission given for accessing user private data for a third party application.

The user is in full control of a given service once it has been installed and configured on the device – MExE requires the terminal to support the necessary functionality for the user to launch, suspend, and delete services. Additionally, the provider of the service may also delete or suspend a service. The user should be able to access information about resident applications and services, for example application size, version number, and status, i.e. whether the application is currently executing or suspended.

9.2.4 The Generic MExE Architecture

The MExE architecture is not very different from that of the Internet and since MExE supports standard Internet protocols such as HTTP, the MSE may include web servers. Since a MExE device may also offer services to other MExE devices, essentially all

MExE compliant terminals are themselves part of the MSE. Figure 9.3 illustrates the generic MExE architecture. A MExE device may connect to the MSE directly or through a gateway. The access network itself may be both wireless and/or fixed; however, it is envisaged that the majority of mobile devices would connect to the MSE over a wireless network. As noted earlier, MExE is bearer independent and it is anticipated that the majority of future MExE devices may have support for multiple wireless access methods.

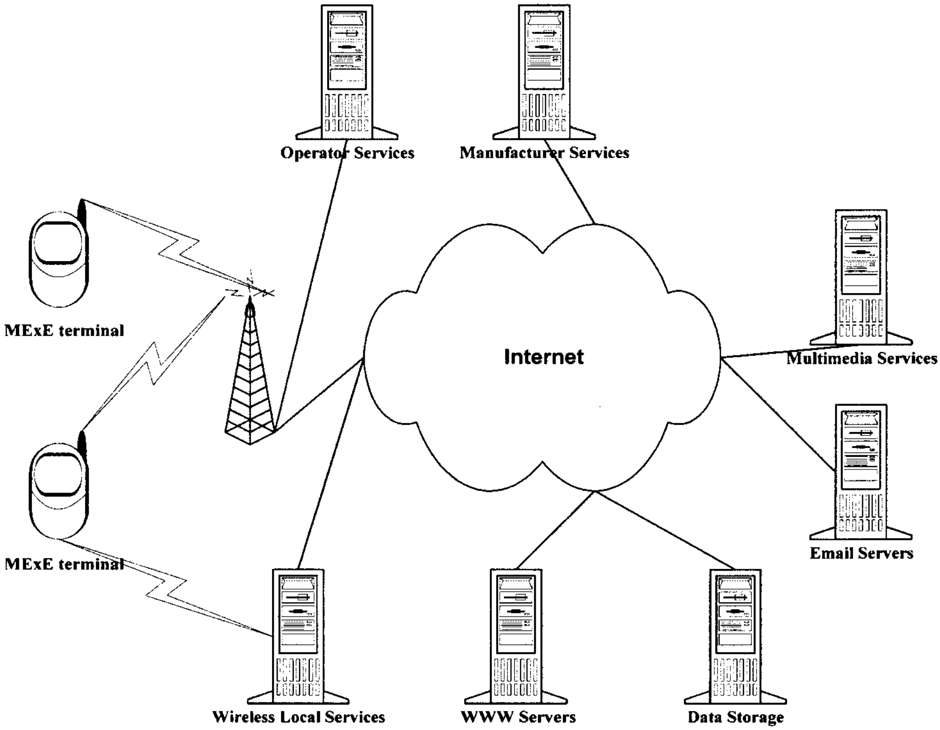

Figure 9.3 MExE generic architecture

The MSE may contain a host of different services offered by the operator, manufacturer, and third parties such as multimedia messaging, WWW access, synchronization, protocol translation, data storage, and security. A MExE terminal with air interface SDR capabilities could use the MSE to download core software to the terminal and perform a handset upgrade.

The exact location of a service within the MExE architecture will depend on the service provider, i.e. some of the operator-specific services will be located within the operator's access network while third party services are likely to be available from servers that are in the public domain.

9.3 Classmarks and Associated Technologies

A MExE Classmark is essentially an execution environment based on an existing technology within the MExE security framework; additionally it also supports capability negotiation.

These additional requirements are there mainly to mitigate interoperability issues. The execution environment itself is specified outside of MExE. The generic architecture of a MExE terminal is shown in Figure 9.4. Normally the 3GPP MExE group tracks the activities of these other organizations (WAP Forum for example) and makes appropriate changes to the specification to reflect any new developments.

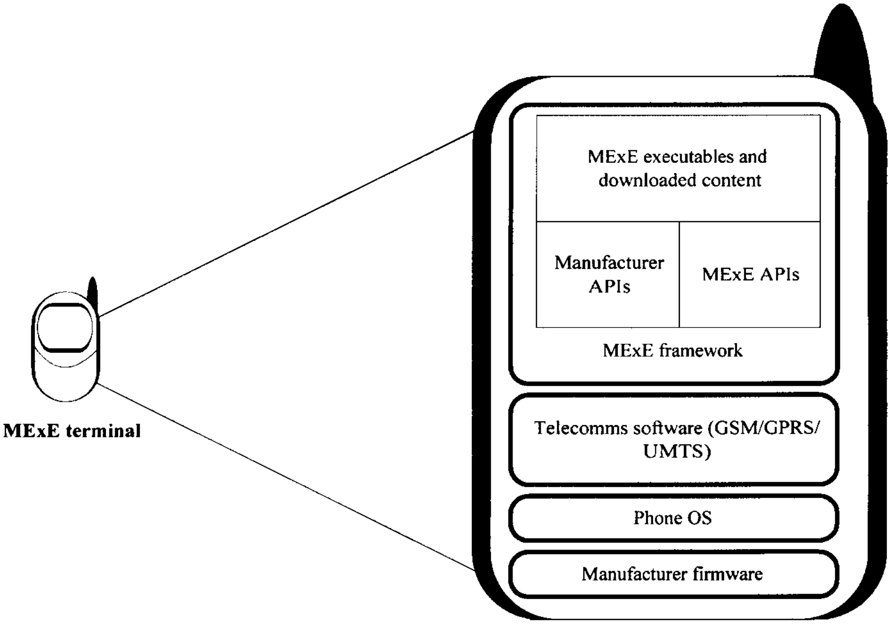

Figure 9.4 MExE terminal architecture

To date three different MExE Classmarks have been defined, which support different features and services depending on the capabilities of the underlying technology. Hence two MExE devices belonging to two different Classmarks could support different services and hence behave differently. It is quite possible for a device belonging to one Classmark to be more efficient in its implementation of security domains.

9.3.1 Classmark 1 Devices

A MExE Classmark 1 device is based on WAP, as defined by the WAP Forum [6]. WAP is a wireless-friendly open protocol standard that may be used to deliver Internet-like services to the mobile terminal. WAP is independent of the underlying bearer technology and can operate over circuit- or packet-switched networks, GSM, GPRS, or short message service (SMS) for example.

9.3.1.1 Fundamentals in WAP

The WAP specification essentially covers five different areas:

WAP programming model. The basic WAP architecture consists of the WAP client, the WAP gateway, and the content server, which may essentially be a web server. The WAP architecture is very similar to the WWW model and re-uses a number of Internet technologies. For example the interaction between the WAP gateway and the content server takes place over HTTP/1.1.

WML language. The wireless markup language (WML) is similar to XML, however it is optimized for resource-constrained devices with limited display capabilities. It also takes into account that a handheld device may only have a very limited set of input devices; for example it is most likely that a full size keyboard would not be available. WML is also wireless-friendly, compared to its Internet counterpart HTML, since it has a smaller number of tags. More information on WML may be found in the WAP specifications [2].

WAP browser. A WAP browser (or a microbrowser, as it has become popularly known) is the equivalent to a web browser in the Internet model. The browser specification refers to how WML and WMLScript should be interpreted once on the mobile terminal. The microbrowser presents an interface to the user to interact with the WAP terminal.

WAP protocol stack. WAP defines a set of optimized protocols on and above the transport layer for wireless networks. This enables all WAP applications to be bearer independent, as mentioned previously.

Wireless telephone application (WTA) framework. WTA is a framework whereby WMLScript applets may be used to provide telephony-related services. These applets may be downloaded to the WAP device from a server on the network. Some example services include call forwarding and intelligent call handling.

9.3.1.2 WAP and MExE Classmark 1

The MExE specification mandates that all MExE Classmark 1 devices should be compliant to the WAP specification. That means that all mandatory features in the WAP specification are also mandatory for a MExE Classmark 1 device and the same applies to the optional features. The real difference between a WAP device and a MExE Classmark 1 device lies in the security framework, together with some further requirements on service management as identified previously in Section 2. A MExE Classmark 1 device also makes use of the certificate profiles and formats as defined by the WAP Forum. These are yet to be defined within the specification.

As it currently stands, the WAP specification does not support a domain-based security model. Therefore, it is not essential for a MExE Classmark 1 device to support the three MExE security domains. However, if these are to be implemented, then they should comply with the MExE specification.

9.3.2 Classmark 2 Devices

MExE Classmark 2 devices are likely to be the more feature-rich MExE devices within the current specification. Also it is Classmark 2 devices that are most likely to have support for advanced SDR capabilities. Based on the PersonalJava [7] specification from Sun Microsystems, a Classmark 2 device contains a Java virtual machine (JVM) and an optimized set of Java class libraries.

However, PersonalJava on its own does not support APIs for telephony-based services. These telephony-specific features are specified as part of the JavaPhone [8] API specification; this contains a large number of APIs. A MExE Classmark 2 device will support the wireless profile within the JavaPhone specification, including APIs that are responsible for handling an address book, calendar, datagram, and power monitor. The rest of the APIs within the JavaPhone specification may be optionally supported, including, for example, call control, phone capability, or SSL APIs. Figure 9.5 illustrates the architecture of a Classmark 2 device.

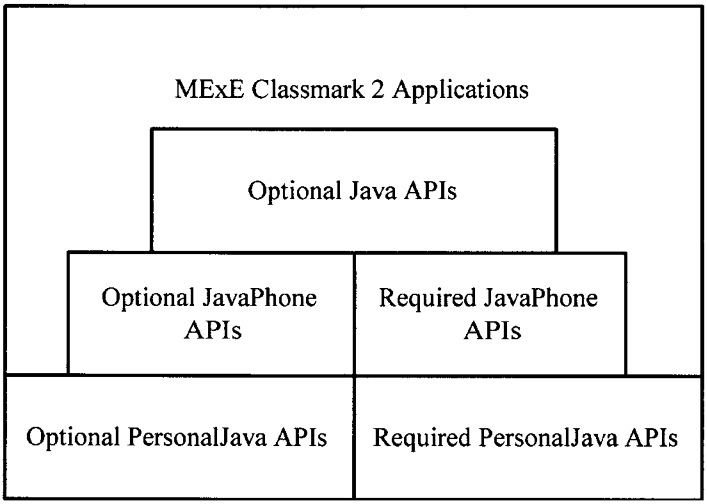

Figure 9.5 Classmark 2 device architecture

PersonalJava has support for fine grain security, in addition to the standard untrusted sandbox model. This enables Classmark 2 devices to support the three security domains specified in the MExE specification; indeed, Classmark 2 devices are the only MExE devices within Release 4 that could support the security domains.

9.3.3 Classmark 3 Devices

Classmark 3 was specified within Release 4 to introduce Java 2 micro edition (J2ME) to the MExE specification. The J2ME represents the compact implementation of Java that sits alongside J2SE (Java 2 standard edition) and J2EE (Java 2 enterprise edition). Recently J2ME has received tremendous attention from developers. Unlike its heavier counterparts, J2ME addresses a vast number of resource-constrained devices, such as smartcards, mobile phones, and set-top boxes. The architecture of a Classmark 3 device is shown in Figure 9.6.

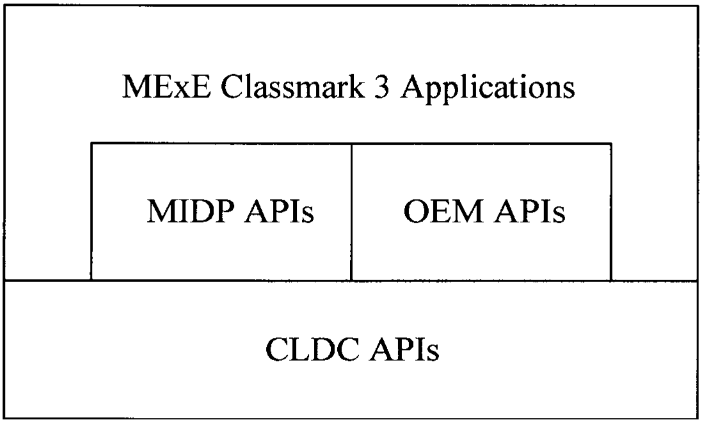

Figure 9.6 Architecture of a Classmark 3 device

9.3.3.1 J2ME Configurations and Profiles

The fact that J2ME covers a wide range of devices makes it difficult to include all the required APIs in a single J2ME implementation. In order to address this problem effectively, J2ME contains a number of configurations and profiles. A *configuration* consists of a JVM together with a set of APIs that define a particular class of device based on available hardware resources. A *profile*, on the other hand, contains APIs that are more specific to a given device's functionality. For example, it would not be useful for a set-top box to have a number of APIs that are dedicated for call handling and call control. However, these APIs are essential for a mobile phone. Therefore, such device-specific APIs may be bundled into a profile rather than including them in a configuration.

Connected Limited Device Configuration (CLDC)

J2ME currently has two configurations, both aimed at connected devices. They are connected device configuration (CDC) and connected limited device configuration (CLDC). As the name suggests, CLDC is primarily aimed at devices with limited memory, processing, network access, and display characteristics. Hence the virtual machine specified in CLDC [9] is rather compact (in the order of kilobytes) compared to other JVMs and hence it is called the kilobyte VM or KVM. The APIs contained in CLDC are common to a certain class of devices, for example devices that are heavily resource-constrained, like a smartcard or a mobile phone. Since CLDC specifies APIs that are widely applicable, there are no optional APIs defined for CLDC.

Mobile Information Device Profile (MIDP)

All APIs that support device-specific features are contained in profiles. CLDC currently has two profiles defined, the PDA profile and the mobile information device profile (MIDP); Classmark 3 is based on MIDP.[1] However, the choice of MIDP [10] imposes some restrictions. For example, the current MIDP specification does not support fine grain security, with

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[1] The MIDP specification at the time of this writing is 1.0.

the result that Classmark 3 devices cannot support the three security domains. This limits all Classmark 3 applications to be untrusted, implying a set of stringent security requirements. In addition, MIDP does not support the transmission of dual tone multifrequency (DTMF) tones. There are also some restrictions in handling the phonebook functionality. It is expected that later versions of MIDP will contain support for fine-grained security and other features that will be able to support the three security domains, together with a host of other features.

Additional Classmark 3 Functionality

A Classmark 3 device may also contain additional features to what is defined in CLDC and MIDP specifications. These features may be introduced by adding additional APIs to the device on top of what is already defined in MIDP and CLDC. These APIs will normally appear in the form of original equipment manufacturer (OEM) classes. MExE does not require any OEM classes to be defined within a Classmark 3 device; however, a Classmark 3 application may use OEM classes to perform additional features. These applications that make use of OEM classes will not be portable between different MExE devices from different manufacturers. MExE requires all such features, added through OEM classes, to comply with the MExE security model.

9.4 Security

A reconfigurable terminal will support a number of functions that could be easily exploited by hackers if proper measures were not taken, SDR capability being one of them. The ability to download applications onto a terminal and execute them locally poses considerable potential risk. In addition, giving access to terminal telephony functions to these applications is even more worrying! A naÏve user could easily download a virus on to the terminal unknowingly which could not only damage the terminal, but could also affect the network services. Once one terminal was infected, the virus could propagate itself within the network infecting other devices that trust the originally infected terminal, resulting in widespread inconvenience and loss of confidence in the technology. The cost of recalling hundreds of thousands of terminals could run into millions of pounds, in addition to the loss of revenue due to malfunctioning terminals. These risks are very real in the Internet today, as it has been shown time and time again that the average user is incapable of making security-related decisions. A classic example of this was the widely publicized ‘I Love You’ virus in 2000.

MExE can potentially support applications from any developer as long as they are written for one of the supported Classmarks. These applications will have varying capabilities and hence the requirement on local resources will also vary. However, from a technical viewpoint there are certain functions and services that are best offered by the network operator. Similarly some services are best suited to be offered by the device manufacturer. Based on such assumptions, the natural choice for SDR activities may be under the supervision of the manufacturer.

It could be that these services will require greater flexibility in accessing local resources on the terminal. In order to accommodate this flexibility in resource allocation for different application developers MExE requires a robust security model.

9.4.1 The Security Model

In order to tackle this formidable challenge, MExE specifies security requirements in addition to the mechanisms provided by the execution environment. This means that regardless of the security features provided by a specific software platform, MExE specifies a security framework that should be supported by all MExE devices regardless of the Classmark. Therefore, all MExE terminals have the same security architecture. This could be interpreted as a security blanket around the execution environment.

Primarily, MExE requires for all downloaded applications to have one of two trust statuses, trusted or untrusted. The digital signature on the application determines the trust status of an application. Once a signed application is downloaded to the terminal, it is authenticated using a PKI. In MExE the trust status essentially decides the capabilities of a given application. For example, trusted applications may have access to user private data, with user permission, while untrusted applications are barred from accessing this information altogether.

The MExE security model provides a certain degree of flexibility in allocation of local resources and access to functionality on the terminal. This is achieved by supporting three distinct trusted security domains. One of these is reserved for applications that are trusted by the operator. A second domain is reserved for applications that are trusted by the manufacturer. The third domain is for trusted third party application developers. In addition to these trusted domains, MExE also supports untrusted applications in what is known as the 'untrusted area'. Figure 9.7 highlights the three MExE security domains and the untrusted area. SDR capabilities can only be supported if the terminal supports the three secure domains.

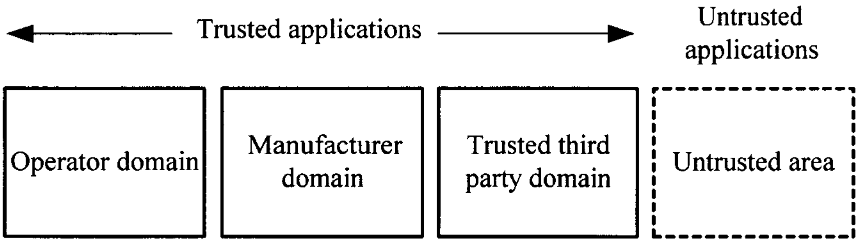

Figure 9.7 MExE security domains

9.4.2 User Permissions and Interactions

The domain-based security model of MExE gives a certain degree of flexibility related to the capabilities of different applications. It divides applications into three different categories and assigns them to security domains depending on the origin of the application. However, the application's association with a security domain does not automatically grant permission to all the capabilities of the domain. The user has to grant permission explicitly against each of the capabilities on a domain.

MExE enforces this by introducing a permission framework that applies to all applications regardless of the domain in which they reside. This approach takes into account that different applications will require permission for a wide range of tasks. There could be applications that perform the same task a number of times and thereby force the user to grant permission for the same task over and over again. This would be a real nuisance to the user and could render MExE unusable. At the same time there could be applications that are simply long lived; once activated these could potentially execute in the background for months, if not for the entire lifetime of the terminal. They may require network access or access to user private data from time to time. One example of such an application would be a terminal management application from an operator. In order to address the requirements of a range of applications, the permission model includes three different types of permissions as shown in Table 9.2.

Table 9.2 Permission model showing three different types of permission

Permission type	Description
Single action	The user gives a single permission to the MExE executable for a specified action; if the executable subsequently wishes to repeat the action it must again request the user's permission for the identified subsequent action.
Session	The user gives permission to the MExE executable for the specified action during a specific run time session of an executable, and the executable subsequently uses the user's original permission for the identified subsequent actions whilst the executable session is still running.
Blanket	The user gives blanket permission to the MExE executable for the specified action, and the executable subsequently uses the user's original permission for the identified subsequent actions whenever the executable is running (not applicable for uninstalled applications).

It is up to the user to decide and grant the correct permission type to the application concerned. For example, the terminal management application from an operator could be granted blanket permission for network access and user private data. MExE allows these permissions to be combined into a single request as long as the user is informed of the individual actions this permission applies to. However, MExE enforces certain restrictions on some applications; for example, it does not allow blanket permission to be issued to an uninstalled application.

9.4.3 Capabilities of Different Security Domains

The three security domains – operator, manufacturer, and trusted third party (TTP) – have different capabilities. However, all domains provide their applications with access to network resources and user private data once the user has granted the appropriate level of permission. Even though strictly not a domain, the untrusted area also has some limited capabilities, for example access to the user interface and also to some network resources to exchange data with an external device once user permission is granted. However, applications in the untrusted area do not have access to any terminal functionality, for example support for core software download, user private data, and terminal data or network properties. The capabilities of the trusted domains are outlined in Figure 9.8.

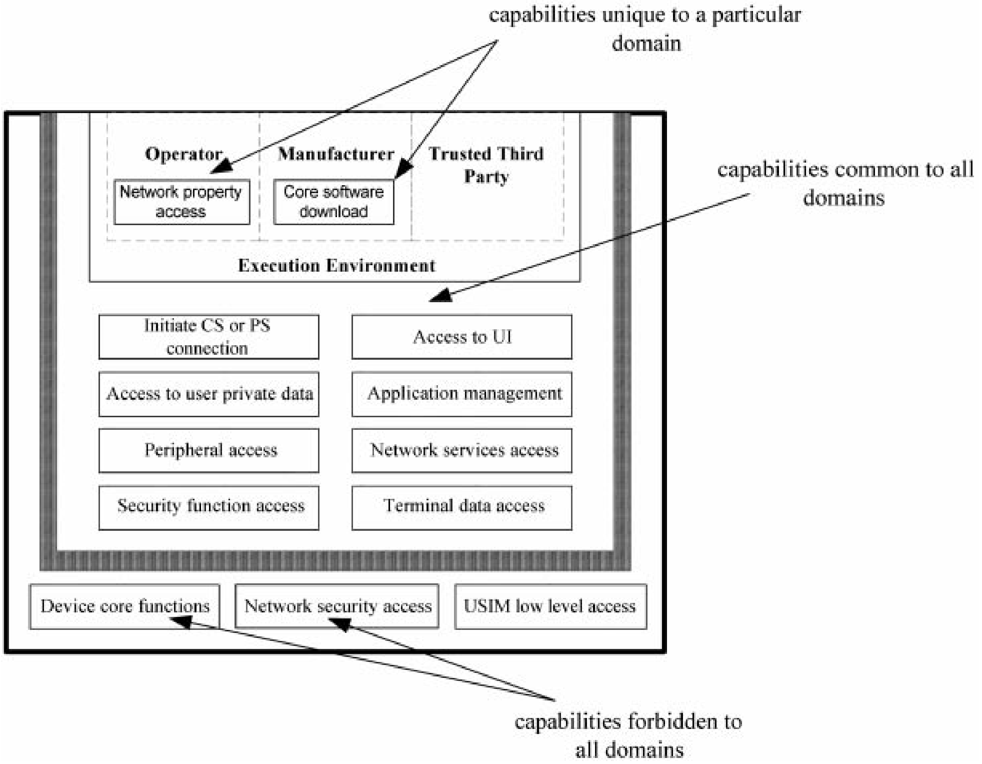

Figure 9.8 Capabilities of the trusted domains

9.4.3.1 Operator Domain

Applications that require access to the operator domain functionality must have a trust relationship with the operator serving that MExE device (the term 'operator' is defined in MExE to be the provider of the 'Home Environment' for that particular MExE device). The operator domain applications must be signed either by the operator or by a third party trusted by the operator. This requires all application signatures in the operator domain to chain up to the operator root public key (ORPK) on the device. The ORPK can reside either on the SIM [11]/USIM [12] or on the terminal.

There is no specified limitation on the number of applications that can be associated with the operator domain; any such restriction is due to resource constraints on the device. However, MExE specifies that there may be only one active ORPK on the device at any given time. This does not prevent any other valid (as in not expired) ORPKs residing on the terminal or on the USIM, provided they remain dormant. From a security and an ease of management viewpoint it is likely that the ORPK would be stored on the USIM. For instance, the ORPK on the USIM could be managed via an over-the-air (OTA) server. In the event that an ORPK is present on both the terminal and the USIM, the ORPK on the USIM would always take precedence; in this scenario, the ORPK on the terminal would be disabled until such time that a USIM without an ORPK is inserted in the terminal.

Applications in the operator domain have privileged access to network properties. For example, they may query and identify the home network to which the device is currently attached. Also, operator applications may select between networks. For example, an application in the operator domain can make the terminal register with a different network service provider provided the request is accepted (this does not change the ownership of the operator domain since the Home Environment has not changed). In addition, applications may be able to access the international mobile subscriber identity (IMSI) number (a 15-digit number that identifies all mobile users uniquely) stored on the USIM or on the SIM.

9.4.3.2 Manufacturer Domain

Manufacturer domain applications must have trust relationship with the terminal manufacturer. Such applications may not be directly written by the manufacturer, but perhaps by application developers that are trusted by the manufacturer. Applications associated with the manufacturer domain should have a certificate chain that terminates at the manufacturer root public key (MRPK). As with the operator domain, MExE specifies that there can be only one active MRPK in the terminal. The MRPK should be securely stored on the device. Nevertheless it is possible to have other valid MRPKs (probably a backup MRPK installed at the time of manufacture) on the terminal, provided that they are not active. In the event that the current MRPK gets compromised or expires, a backup MRPK can be enabled to replace it using a secure mechanism that may be proprietary to the manufacturer.

Applications in the manufacturer domain can have access to privileged capabilities provided by the terminal manufacturer. These are based on the privileged access to resources on the terminal functionality. For example, the manufacturer domain has the capability to download core software to the terminal, allowing terminal reconfigurability such as a new air interface or voice codec. In addition, an application in the manufacturer domain could have access to special APIs that are specific to that manufacturer. These can be included in the terminal as OEM classes. MExE itself does not specify any such OEM classes, since applications that use them would be manufacturer specific and would not be interoperable. However, if implemented, MExE requires all such OEM classes to obey the MExE security model.

The MRPK of a terminal would normally be stored on the terminal in a secure area. MExE itself does not specify a secure mechanism for storage. However, it is vital that the integrity of the MRPK is not compromised. If compromised, this would enable a malicious party to download applications that could potentially damage the terminal or the network. The management of the MRPK is also not specified in MExE. Therefore, it is left up to the manufacturer to implement a secure method to enable/disable a MRPK on the terminal.

9.4.3.3 Trusted Third Party Domain

The trusted third party (TTP) domain contains a similar set of capabilities, without the access to either core software download or network properties. However, there are more stringent restrictions on the capabilities themselves that need to be met. Nevertheless, this is the domain with the potential to host the greatest number of applications from a large developer community. Theoretically there are no limitations on the number of parties that could write applications to the TTP domain. The only requirement on the application developer is that they be trusted by one of the RPK owners in the TTP domain. Unlike the operator and manufacturer domains, MExE does not limit the number of RPKs associated with the TTP domain; instead this would generally depend on the resource constraints of the terminal. TTP RPKs could be stored either on the terminal or on the SIM/USIM.

The TTP domain and the Role of the Administrator

The TTP could potentially have tens of RPKs associated with it. These RPKs could belong to certification authorities (CA), banks, application developers, or even operators and manufacturers. They may be installed at the time of manufacture of the terminal or alternatively may be downloaded to the terminal at a later time. In either case, it is important to authenticate these RPKs before they are installed in the terminal and trusted. In order to exercise some control over this process MExE introduces the role of an ‘administrator’.

The administrator is responsible for authenticating the RPK in the TTP when they are installed for the first time. The administrator of the terminal should trust all parties that are allowed to have their RPKs in the TTP domain (the exact mechanism is described shortly – see (b) below). This is achieved using an administrator RPK (ARPK). The ARPK could be stored either on the terminal or on the USIM. The operator, the manufacturer, the user of the terminal, or a third party could assume the role of the administrator – the user decides this. If the operator is chosen as the administrator, the operator could use the ORPK to administer the TTP domain. Similarly, if the manufacturer is chosen as the administrator, the MRPK could be used in place of the ARPK. It should be noted that the ARPK itself is not used to authenticate applications in the TTP domain.

Management of RPKs in the TTP domain

The administrator role is easily misunderstood by the readers of the MExE specification, possibly due to the complexity associated with the administrator mechanism. However, the role of the administrator in MExE is to manage the RPKs in the TTP domain. This includes the authentication of a RPK when it is installed on the terminal. Also, if one of the RPKs in the TTP domain gets compromised it is the responsibility of the administrator to disable the RPK before any damage is done either to the terminal or to the network.

This is achieved using certificate configuration messages (CCM). Essentially, when it is known that one of the RPKs in the terminal has been compromised, the administrator sends a signed CCM to the terminal. Once the CCM arrives on the terminal it is verified using the ARPK to check for its authenticity. If the CCM verifies correctly, the named RPK is disabled.

The concept behind a CCM is thus similar to a certificate revocation mechanism for RPK, the difference being that it is not used every time a RPK is used to verify an application. CCMs are only used within the TTP domain and are not applicable in the other two security domains.

9.4.3.4 The Untrusted Area

It is expected that a large number of applications available to MExE users will not be signed, for a variety of reasons. It may be that the developer does not have the capability or the financial might to deal with a well-known certification authority that would certify the applications on the developer’s behalf, or it may simply be that the application itself does not require access to privileged resources on the terminal. It may be a simple game, which requires access only to the display and keypad. It is this type of application that the untrusted area is designed to cater for.

The fact that the user is free to download applications from any source means that the naÏvety of the user could easily be exploited by hackers to propagate malicious content. All in all these factors make the untrusted domain the weakest link in the MExE security model and it is thus important to restrict the capabilities of the applications in the untrusted domain accordingly.

The approach taken in MExE has been to reduce the access to terminal functionality by restricting untrusted applications to a sandbox, the capabilities of which are explicitly identified in the MExE specification – anything that is not in the specification is not permitted. Further, the majority of these capabilities themselves are subjected to explicit user permission. For example, an untrusted application may establish a voice connection provided the user is consulted first. MExE also requires the number to be called to be displayed to the user by a provisioned functionality of the terminal. This is to ensure that the application does not fool the user by displaying a different number to that which is dialed. Even though asking the user might not be the best approach to take from a security point, it is the only way to support untrusted executables within a resource-constrained environment like MExE. The capabilities of the untrusted domain are illustrated in Figure 9.9.

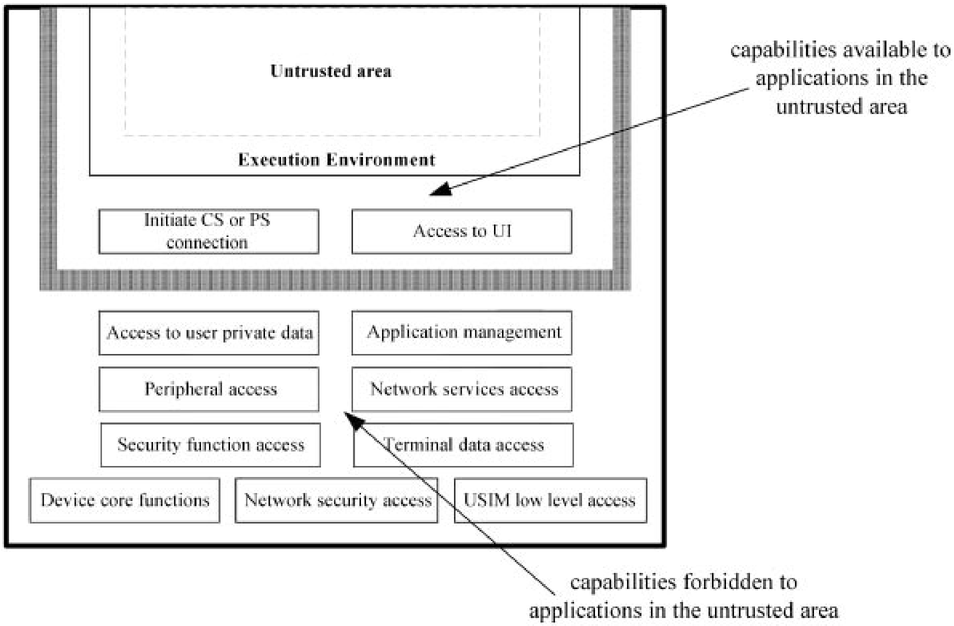

Figure 9.9 Capabilities of the untrusted area

9.4.4 Verification of Signed Content

The MExE security model is based on a PKI to authenticate signed content downloaded to the terminal. The verification of the application signature and any intermediate certificates is an essential part of the security model. It ensures that all applications have a valid signature and a certification path to one of the RPKs on the terminal. It also checks for the integrity of the applications to make sure that applications have not been tampered with, either during the download process or whilst stored prior to download. In the current specification the signature verification process also determines the secure domain in which a signed application should execute – i.e. it is responsible for assigning applications to the operator, manufacturer, or TTP domain.

9.4.4.1 The Signature and Certificate Verification Process

All MExE applications upon download to the terminal are subjected to the signature and certificate verification process. This specifies the logical process to be followed when verifying the application signature and the intermediate certificates of the downloaded signed package. The order in which the individual processes should be implemented is not strictly specified, the emphasis being that the final outcome of the process should be consistent with the specification. The signature and certificate verification process is outlined in Figure 9.10.

When an application is downloaded to the terminal, the terminal checks whether the application contains a signature. An application with a signature is further examined in a number of steps, which include the availability of a complete set of intermediate certificates and a valid RPK on the terminal or on the SIM/USIM. This ensures that all the necessary certificates are in place to carry out the verification process. If there are missing certificates the process is terminated and the package is assigned to the untrusted area. The process also determines whether the terminal supports secure domains; if they are not supported the applications are assigned to the untrusted domain.

Once the application signature and the certificate chain have been verified, the application is assigned to one of the three trusted domains. The assigning is done according to the RPK that was used to verify the certificate chain. If the ORPK was used during the verification, then the application is assigned to the operator domain and likewise if the MRPK was used the application is assigned to the manufacturer domain. Finally if one of the TTP RPKs was used the application is assigned to the TTP domain.

It should be noted that MExE allows certificate processing without having to support the three secure domains. The idea is to have ‘authenticated’ applications in the untrusted domain. This is desirable to prevent false accusations against application developers if other applications misbehave in the untrusted domain.

Formats and Intermediate Certificates

The current specification does not contain any certificate format information, however, it is expected that a wireless-friendly profile of X509 [13] will be used eventually. The most likely profile to be referenced is the WAPCert profile [2]. The current specification already contains a MExE-specific X509v3 extension for restricting network access to applications. This extension is mandated within the operator domain and remains as optional in the manufacturer and the TTP domain. This extension could be used to disable network-specific capabilities, for example setting up a connection.

The public key certificate standard number 15 [14] (PKCS#15) specifies a file and directory format for storing security-related information and cryptographic tokens. The current MExE specification (in Annex A) assumes a PKCS#15 file structure and object format when storing and referencing MExE certificates in the SIM and USIM.

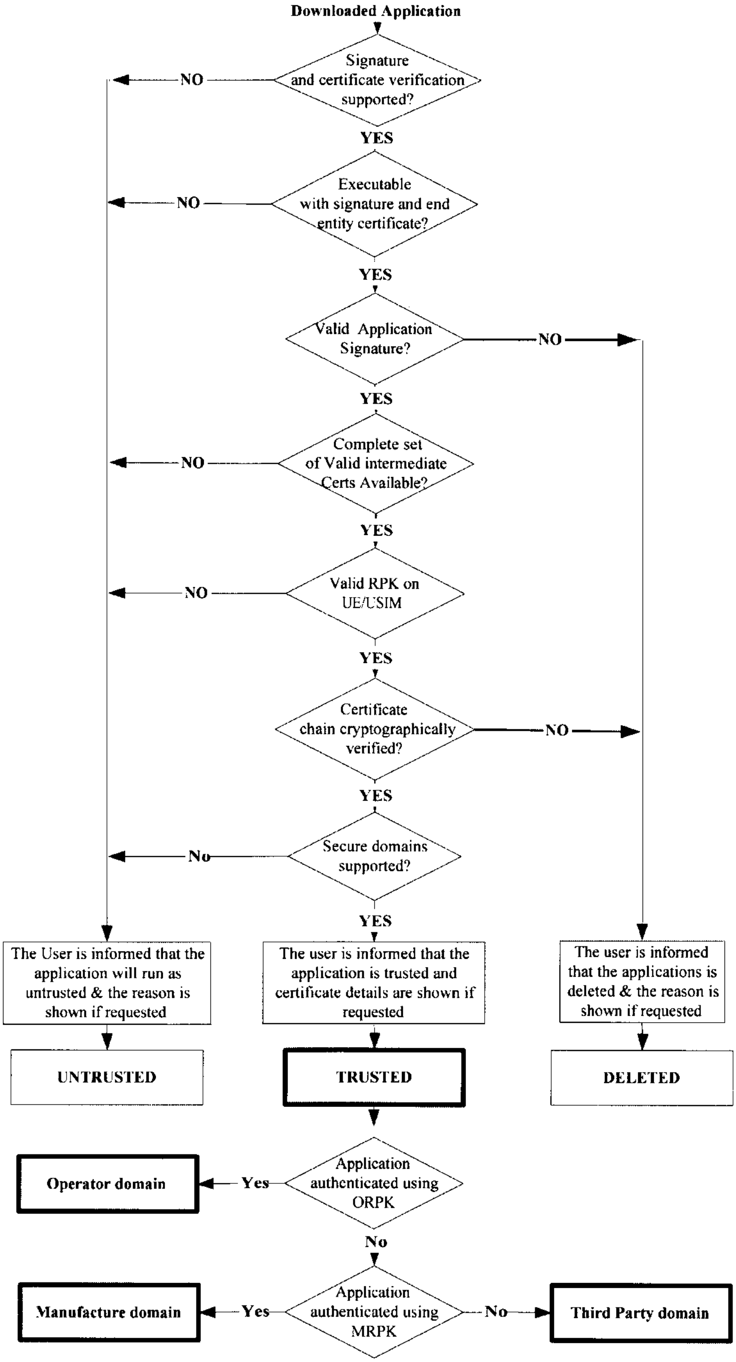

Figure 9.10 Application verification

MExE does not currently specify the way in which the intermediate certificates themselves arrive on the terminal. One option for Classmark 2 and 3 applications is to package them in the Java Archive (JAR) file [15], thereby saving time and resources on the terminal. Alternatively, the JAR file could contain a URL where the certificates could be downloaded. Another method that could be used is for the terminal to download any missing certificates to construct a valid chain to one of the RPKs on the terminal; however, this approach might involve considerable terminal resources.

Certificate Revocation

With hundreds of thousands of developers writing applications for millions of MExE terminals there are bound to be instances where certificates have to be revoked. This is already happening in the Internet world to a certain extent. One such occasion occurred in early 2001 when Verisign mistakenly issued a pair of class 3 code signing certificates to an individual who falsely claimed to be an employee of Microsoft. It is reasonable to expect that this could get a lot worse within an environment similar to MExE. Nevertheless, at present there are no wireless-friendly revocation mechanisms that MExE could reference. Therefore, MExE does not currently mandate certificate revocation.

However, MExE recommends a revocation mechanism for all terminals with support for signed content. Some existing mechanisms include certificate revocation lists (CRL consultation), online certificate status protocol (OCSP), and simple certificate verification protocol (SCVP). Another solution that could prove to be wireless-friendly is XML key management specification (XKMS).

9.4.5 Future Security Developments

There is an initiative within the MExE group to review the current security model to address a number of important issues. The current model assigns applications to security domains depending on the RPK used to authenticate them. This results in two restrictions, namely the inability to share a single PK between security domains. This restriction is added to ensure a unique certification path from the end entity certificate to the RPK; however, such a restriction appears impractical to implement.

Further, the direct association of a RPK with a security domain is inflexible; specifically, it prevents a RPK from one domain from authorizing signed content to another domain. For example, a manufacturer is unable to re-use the MRPK to authorize applications in the TTP domain. In order to do this, the manufacturer is required to have a separate RPK in the TTP domain. The complexity and the management headache associated with generating and distributing RPKs does not make this approach very attractive. Also from an operator's point, a single RPK that could authorize signed content to, for example, the operator and the TTP domain could save valuable resources on the SIM/USIM.

In the event that the MExE group decides to make any enhancement to the security model, it would most certainly consider removing the association of RPKs with security domains. Further, it is likely that MExE would adopt X509 certificates profiled according to the signed content section in the WAP certificate profile.

9.5 Services

9.5.1 Current Status of Terminals

Modern mobile terminals are highly compact and lightweight (due to advances in RF, processor, and battery technologies) compared to their counterparts of 10 years ago. However, apart from this miniaturization, and the addition of a few simple games and basic man–machine interface (MMI) enhancements, the terminal functionality has remained unchanged, i.e. they are still voice centric. In the meantime there has been tremendous growth and increased functionality in the home-computing front. The numerous advances in video and audio compression technologies, together with enhanced 3D graphics, have revolutionized the home-computing environment in the same period.

The steady fall in cost of airtime has also meant that operators are finding it difficult to maintain their average revenue per user (ARPU), a trend which is expected to continue into the foreseeable future. In addition, the mobile phone market is reaching penetration values that are approaching saturation. These factors call for realignment in the strategy that operators should be considering; a simple repositioning in the value chain is not an option here. Operators are seeking new opportunities to offer services other than voice. These new services should allow the operator to add value before delivering it to the end user. A popular option that most operators are considering and have already adopted is hosting service portals; however, a portal does not represent a great opportunity for value addition and nor does it address the issues forcing operators to become nothing more than a bit-pipe.

On the other hand, manufactures are struggling to get products into the market before the technology becomes outdated. In addition, in mature markets the demand for fresh terminals is flattening, mainly due to market saturation. From a manufacturer point of view, after the initial sale of the terminal they are excluded from the value chain.

The convergence of information technology and telecommunications is creating a unique environment, an environment where software applications are emerging as a new commodity in the mobile communications market. It is expected that these applications will in turn generate a considerable demand for data services, something that operators are hoping will boost new bearers like GPRS and eventually 3G.

9.5.2 What MExE Enables?

Terminals complying with the MExE specification can support a wide range of services for the end user. Unlike traditional terminals, the majority of these services will not be based on voice. MExE also promises to be the most suitable candidate with a standardized execution environment to offer secure mobile Internet-based services for mass-market devices. The fact that there are already three Classmarks, and a fourth in definition, means that all major software platforms would be catered for within the framework of MExE. Future releases are expected to contain further Classmarks if the 3GPP MExE group identifies the need for them. This would give the users a wide range of applications to choose from a diverse application developer community.

It is difficult to predict what might be a killer MExE application, however, early signs from developers suggest that downloadable games will be popular. Also on the list are location-based services. The current success of the SMS also indicates the likely importance of instant messaging.

All MExE applications and services may be divided into four distinct categories depending on the location of the application or the service.

- The MExE server in the network – these applications and services reside on a MExE server within the network. The server itself could be located anywhere in the MSE. It could be a web server which the terminal could use to access WWW content. Alternatively it could be a server located within the operator network that offers location information to a MExE terminal.
- A client on the terminal interacting with a MExE server on the network – the client could be an e-mail application on the terminal while the mail server itself is located in the network. Other examples include networked games where the terminal interacts with a gaming server in the network that generates scenarios for the gaming client on the terminal.
- The local MExE terminal – these applications or services could include a downloaded game located on the terminal. Once downloaded the application does not rely on network resources. Similar examples include currency converters or calendars and diaries.
- Another MExE terminal – this is a special instance of the first case above. MExE allows for services to be offered from one MExE terminal to another, on a peer-to-peer basis. However, MExE does not specify any details on this. Therefore, the exact interaction between the terminals, such as master–slave relationships, is outside the scope of the specification. However, it is reasonable to assume that these might change from terminal to terminal and may ultimately be decided by the user.
- Regardless of where the application or the service may reside, the final capabilities are always decided by the MExE security framework subject to user permission.

9.5.2.1 Operator Applications and Services

The owner of the operator domain is the operator that provides the Home Environment to that MExE terminal. This is particularly important when the user is roaming, where some, or the majority, of the network-based services might be offered using a roaming partner of the home network (otherwise known as the serving network).

The operator domain would be the preferred domain for an operator to execute his applications. However, this does not prevent an operator from executing his applications in the TTP domain. In fact this might be the most likely scenario. Apart from applications that require use of the operator network, the majority of other applications would execute in the TTP domain. There is no restriction in MExE regarding executing operator applications in the TTP domain. For example a gaming application could execute in the TTP domain if the operator has a RPK in the TTP domain. This approach gives a flexible way of managing applications. An operator does not have to use the operator domain unless the application requires the functionality of the operator domain.

It is expected that games and multimedia messaging will be some of the earliest MExE applications and services to become available with location-based services and basic m-commerce applications to follow. An important initiative that all operators are looking to offer is branding. A branded terminal would support a unique MMI for that operator. This could be the front end for all operator applications and services, regardless of whether the service itself is located in the network or on the terminal.

An operator application in the operator domain could be used to maintain up-to-date terminal information in the network, such as terminal model, applications resident on the terminal, user preferences, etc. Using this information the operator's customer care centers could help customers overcome the potential complexity of a 3G terminal, for example, by providing remote terminal configuration according to user preferences.

Another important goal that operators are looking to achieve is terminal management. MExE has the potential to be the chosen platform for terminal management in 3G. Similar to the scenario described above, an operator application, the client component of a terminal management solution, could gather information from the terminal for terminal management purposes. This information could prove to be very useful if the terminal develops a fault and the user needs to contact customer care for advice. The customer could download an application onto the terminal to carry out a diagnosis. In addition, if the fault lies in the terminal software, the necessary software patch could be downloaded to the terminal as a fix. Such use of OTA software patches could save operators and manufacturers a considerable amount of money by avoiding the need for terminal recalls. This is essentially based on using the SDR capabilities of MExE terminals. Since SDR capabilities are exclusive to the manufacturer domain, such applications would need to be a joint effort between operators and manufacturers. Such an approach could have alleviated situations such as occurred in Japan in 2001 when DoCoMo had to recall a large number of terminals due to a software glitch.

9.5.2.2 Manufacturer Domain-based Services

A MExE terminal provides terminal manufacturers with the opportunity to become service providers and to maintain a relationship with their customers long after the terminal has been sold. This is clearly an opportunity that terminal manufacturers will not miss. The manufacturer domain represents a powerful and a flexible environment whereby new services can be offered to the customer. Support for SDR capabilities in the manufacturer domain represents a powerful tool for the manufacturers. The ability to download core terminal software to the terminal is perhaps the most attractive feature in the manufacturer domain. Manufacturers may exploit the SDR capabilities in terminals to add new terminal features and upgrade existing ones without having to recall the terminal to the factory. As identified in the previous section, SDR support in MExE could play a crucial role in terminal management. This could also be exploited, both by the operators and manufacturers to give a high degree of customization to the user and could be used to cater for a number of niche markets otherwise left unattended.

The ability to download core terminal software may also be used to shorten the time to launch a new product. The terminal is manufactured with the necessary hardware components and the basic software, together with SDR capabilities. Any additional services or features may be added at a later time once the terminals have been dispatched to the store or after they have been sold. Addition of new features and/or customization may also take place at the time of the sale. Such an arrangement enables the manufacturers and operators to make terminal software a commodity in its on own right.

In addition to SDR-based services, manufacturers can take advantage of the gaming and the multimedia capabilities of the terminals. Even though not portable between different terminals, it is quite possible for manufacturers to offer proprietary gaming software that takes advantage of a manufacturer's specific features added via OEM classes. Using OEM classes, manufacturers can potentially enhance the user experience on certain manufacturer-approved applications.

9.5.2.3 Trusted Third Party Services

MExE opens the terminal capabilities to third party application developers to offer their own applications and services. The standardized nature of MExE means that application developers can write applications for a particular MExE Classmark and be assured that users of that Classmark have the potential to be their customers. This is similar to the current PC scenario, where application developers can write applications for a particular environment on a PC with confidence that all PCs supporting that environment will be able to execute it.

The TTP domain can support a number of RPKs. This makes the TTP more accessible to a wider developer community. As with the other two domains, gaming and instant messaging will prove to be popular applications. In addition there may be services targeted to an individual user – for example, a banking application that allows the user to carry out online banking services. An extension of this could also involve online stocks and share dealing. The TTP domain may also support m-commerce applications, both online and at point of sale (POS). An example of a POS transaction could be the purchase of a train ticket using a micropayment client on the terminal. The electronic ticket could be sent to the terminal over a Bluetooth link, to be stored for later use. The most likely Classmark that could support applications of this complexity is Classmark 2.

9.5.2.4 Applications and Services Based on the Untrusted Area

The MExE untrusted area has a similar concept to the TTP domain, to open up the services market to third party application developers. However, one distinct difference is that the untrusted area does not require the third party application developer to have access to a PK that has been certified by one of the RPKs already installed on the terminal. This flexibility comes at a cost; these applications are untrusted and would only have restricted access to the terminal functions, as described earlier. This should not be a great restriction, since the untrusted area is targeted at simple applications. These applications may be written and made available to MExE users by an individual developer and does not require large organizations.

Nevertheless the untrusted area can support a number of interesting and useful applications. For example, the untrusted area could support an application that could monitor the stock market on behalf of the user and notify when a set of predefined conditions have been triggered. The notification could occur via the display or through a sound alert. Traffic monitoring and weather updates represent further application examples. Basically the untrusted area can give the user access to information and services that are pretty much in line with what can be done using a web browser without the security. For simple applications and services this should not be a hindrance.

9.6 Conclusions

Whilst originating with a focus on applications download from a service perspective, the standardization of the mobile execution environment makes possible a wide range of capabilities within the context of reconfigurable terminals. The input of the SDR Forum into the standardization process has meant that the standard has developed into a powerful framework which manufacturers will hopefully begin to populate with products over the next few years, with devices of increasing capability and functionality. The example applications made possible within this framework represent a snapshot of thoughts from today – no doubt the creativity of a broad application developer community will result in new services and applications outside of the scope of today's conceptions. Whilst MExE continues to evolve, with a number of the possible future developments outlined in this chapter, what is clear is that the first important steps in SDR standardization have been taken.

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10

European Regulation of Software Radio

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Software radio promises tremendous potential benefits to users and network operators. However, it also poses some profound challenges on a regulatory front. Existing national and regional regulatory regimes are geared to allowing into service radio equipment that has been approved or certified to operate in a certain pre-defined manner. The availability of products that may change their mode of operation, even their transmission frequency or modulation format, after they have been sold and are in the open market demands fresh thinking.

Europe comprises a collection of nation states, each with their own regulatory bodies, unlike the US, for example, where a single regulator, the Federal Communications Commission (FCC), can propose and implement rulemaking. In this chapter we explain how Europe has developed common regulatory positions in the past and describe recent changes in the regime for putting radio equipment onto the market. We then consider the new regulatory issues that software defined radio (SDR) technology raises. We conclude by describing the process by which a common European position is likely to be reached.

10.1 Regulation in the Past

10.1.1 The Terminal Directive: Type Approval

For many years in Europe each country had its own mechanisms for regulating the marketing and use of radio equipment. With the need for free circulation of goods, associated with the advent of the Single Market, new mechanisms were needed. The so-called 'Terminal Directive'[1] was thus introduced to address this situation. The purpose of the Directive was to

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[1] Council Directive of April 29, 1991 on the approximation of the laws of the Member States concerning telecommunications terminal equipment, including the mutual recognition of their conformity (91/263/EEC).

harmonize conditions for the placing on the market of telecommunications terminal equipment. It established a single European market for equipment approved to a common technical regulation (CTR) and gave legal simplification and technical opportunity. Specifically, it dealt with a number of key issues, namely:

- common technical regulations (CTRs)
- harmonization of radio equipment approval procedures
- mutual recognition of conformity tests
- free circulation of terminal equipment, and
- unrestricted connection of telecommunications terminals to public telecoms networks

The Directive followed the European Commission's 'New Approach to Technical Harmonisation' and gave the 'essential requirements' to be regulated. Harmonized standards[2] gave detailed specifications and tests which allowed terminal equipment to be proved to comply with the essential requirements. Adoption of these specifications in a CTR was by means of a European Commission Decision, announced in the European Union (EU) Official Journal (OJ).

CTRs were common technical regulations for telecommunications terminal equipment, established under the 'Terminal Directive'. Arrangements were made for CTRs to be applied throughout the European Economic Area (EEA), as foreseen in a 'Statement of Intent on CTRs'.

The scope of the Terminal Directive was extended by the Satellite Directive, which also modified the essential requirements for safety. The CE marking to be applied to terminals was amended by the CE Marking Directive, with effect from January 1995.

10.1.1.1 What was a CTR?

CTRs were mandatory regulations adopted by the European Commission (EC). The technical content of the CTR covered only the 'essential requirements' as defined by Articles 4 and 6 of the Terminal Directive. Consistent with the World Trade Organization (WTO) undertaking (previously the General Agreement of Tariffs & Trade (GATT) undertaking), these regulations were based upon international or European standards, as appropriate. The regulations identified which clauses of the base standards were applicable to type certification.

In practice, the CTR consisted of two parts:

- *A Commission Decision:* which contained only the regulatory requirements and references to the TBR where the 'essential requirements' could be found. The Commission Decision was published in the form of an announcement in the Official Journal of the European Communities (the OJ).
- *A Technical Basis for Regulation (TBR):* in which the specifications and tests necessary to ensure conformance with the 'essential requirements' were individually identified. The TBR was considered as a harmonized standard, i.e. it was not to contain any country-specific requirements. The TBR was normally drafted and published by the European Telecommunications Standards Institute (ETSI) under a mandate from the EC, using the same approval procedures as those for a European standard.

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[2] 'Harmonized standards' within the meaning of the Directive are those prepared and adopted on a European basis on a remit from the Commission, with any conflicting national standards being withdrawn – ENs and TBRs can be examples of such harmonized standards.

10.1.1.2 Essential Requirements for Terminals

The question is, what was an essential requirement? In the case of terminals intended for connection to a public telecommunications network, Article 4 defined the essential requirements as:

- user safety, in so far as this requirement was not covered by Directive 73/23/EEC
- safety of employees of public telecommunications networks operators, in so far as this requirement was not covered by Directive 73/23/EEC
- electromagnetic compatibility requirements, in so far as they were specific to terminal equipment
- protection of the public telecommunications network from harm
- effective use of the radio frequency spectrum, where appropriate
- interworking of terminal equipment with public telecommunications network equipment for the purpose of establishing, modifying, charging for, holding, and clearing real or virtual connection
- interworking of terminal equipment via the public telecommunications network, in justified cases

More or less all of these requirements applied to a terminal, depending on whether or not it was a radio terminal, except for Article 4(g), for which an additional decision in ACTE[3] was needed for the so-called ‘justified case’.

10.1.2 The Regulatory Bodies and Advisory Committees Involved

Application of the CTR was the prerogative of those bodies having regulatory powers within the geographical area in which the CTR applied. The CTR was adopted by the EC, acting in accordance with the Terminal Directive. The CTR could also be applied by the European Free Trade Association (EFTA) countries and relevant bodies in third countries with which agreements had been concluded on the basis of a mutually satisfactory understanding (Directive Article 10.5). The EC was responsible for the administration of the procedures necessary for the production of CTRs.

To assist the bodies in these matters, two advisory committees were created:

ACTE (Approvals Committee for Terminal Equipment): which was responsible for overseeing the production of the CTR, giving a formal opinion on the CTR for adoption by the bodies, and advising the bodies of any technical, regulatory or transitional problems which may have existed.

TRAC (Technical Regulations Applications Committee): assisted in the drafting of the scope statement, overseeing the production of the technical content of the TBR (in cooperation with ETSI), and advising the EC of any technical, national regulatory or transitional problems which may have existed. A ‘Statement of Intent’, between the EC and the members of TRAC, outlined the role of TRAC as an advisory body for the implementation of CTRs. It was an important function of TRAC to provide a forum for consensus building, which assisted in the creation of a single area of application for CTRs.

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[3] Approvals Committee for Terminal Equipment Committee (ACTE) consisting of the administrations of the EU Member States acts as an advisory committee to the European Commission on regulatory matters in the telecommunications sector (see Section 1.2).

10.1.2.1 Notified Bodies, Test Houses, and Conformity Assessment[4]

Once published, the CTR was applied for new approvals by 'notified bodies' approved throughout the area of geographical applicability. Each notified body acted independently, but a common understanding of the application of the CTR could be formed by notified bodies through guidance from TRAC and discussions in a forum, such as the Association of Designated Laboratories and Notified Bodies (ADLNB), which was recognized by ACTE.

A terminal manufacturer (or his authorized representative established in the European Community) selected a notified body to determine the conformity of his new product with the essential requirements of the Directive. The notified body was provided with the results of the tests made at the manufacturer's request by an independent test laboratory, or 'test house', together with a representative specimen of the terminal equipment, or 'type'. The notified body then determined conformity of the type with the CTRs (essential requirements) applicable to the intended purpose. Only after the notified body had determined conformity with the essential requirements and provided the manufacturer with written confirmation (type examination certificate) could the equipment be placed on the market.

If at a later date the manufacturer decided to make any design changes, for whatever reasons (e.g. to reduce product cost), such modifications to the equipment needed to be reported to the notified body. In such cases the notified body had to assess the modification and decide whether or not a new type examination was required, which involved a full suite of tests being made in a recognized laboratory, and a new test report and new specimen being submitted for examination to the notified body. A new type examination certificate issued by the notified body was required before the modified equipment could be placed on the market. This process was, as a rule, time-consuming, but gave the manufacturer the advantage of being sure that his equipment met the essential requirements.

10.1.2.2 Summary

In order to meet the requirements of the type approval regime, the manufacturer or person responsible for placing the equipment on the market had to follow a number of steps:

- He identified, either on his own or with the help of a notified body, which CTR was applicable for the intended purpose of the terminal equipment. If there was no applicable CTR, he needed to contact the national notified bodies and comply with the national requirements. This possibly meant having to contact one national notified body for each EU Member State and follow the national procedures (laboratory tests, notified body certificates) for each equipment type.
- He tasked an independent laboratory with carrying out the relevant tests in order to verify conformity with the essential requirements defined in the applicable CTR.
- He produced a representative specimen, or type, for submission to a notified body and confirmed the conformity of the terminal equipment to be manufactured with the type.
- He submitted the laboratory's test report and the type to a recognized notified body, together with an application for a type examination certificate, i.e. confirmation of conformity with the essential requirements.

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[4] Article 9 of the Terminal Directive.

- Once he had received the type examination certificate from the notified body, he could place his equipment onto the market.

This procedure meant that conformity with the essential requirements was the responsibility of the notified body, and not the manufacturer. However, the procedure could be very time-consuming and could lead to unforeseen and highly undesirable delays for the manufacturer in launching a new product.

10.2 Regulation Today

10.2.1 The R&TTE Regime

In light of the European Community's key objective of creating an open single competitive market, a regulatory regime for radio equipment and telecommunications terminal equipment allowing manufacturers greater flexibility in marketing their products was established by the R&TTE Directive – Directive 1999/5/EC of the European Parliament and of the Council of March 9, 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity. As a result, the Terminal Directive regime was superseded in April 2000 by the R&TTE regime.

Key to the new regime are essential requirements which equipment within the scope of the Directive must satisfy before it may be placed on the single market – these essential requirements differ from those under the previous regime. A more fundamental difference is that, subject to certain conditions, manufacturers may declare compliance with the essential requirements themselves, without having to consult a notified body, and therefore place their equipment on the market without any delay.

10.2.1.1 Essential Requirements

The essential requirements under Article 3 of the R&TTE Directive are specified as follows:

Article 3

> 1. The following essential requirements are applicable to all apparatus:
>
> (a) the protection of the health and the safety of the user and any other person, including the objectives with respect to safety requirements contained in Directive 73/23/EEC, but with no voltage limit applying;
>
> (b) the protection requirements with respect to electromagnetic compatibility contained in Directive 89/336/EEC;
>
> 2. In addition, radio equipment shall be so constructed that it effectively uses the spectrum allocated to terrestrial/space radio communication and orbital resources so as to avoid harmful interference
> and
>
> 3. The Commission may also decide[5] that apparatus within certain equipment classes or apparatus of particular types shall be so constructed that:

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[5] In accordance with the procedure laid down in Article 15 of the Directive.

> (a) it interworks via networks with other apparatus and that it can be connected to interfaces of the appropriate type throughout the Community; and/or that
>
> (b) it does not harm the network or its functioning nor misuse network resources, thereby causing an unacceptable degradation of service; and/or that
>
> (c) it incorporates safeguards to ensure that the personal data and privacy of the user and of the subscriber are protected; and/or that
>
> (d) it supports certain features ensuring avoidance of fraud; and/or that
>
> (e) it supports certain features ensuring access to emergency services; and/or that
>
> (f) it supports certain features in order to facilitate its use by users with a disability.

Hence, as a rule, telecommunications terminal equipment is subject to the requirements of Article 3(1) only, while radio equipment is required to comply with Article 3(1) and, additionally, Article 3(2).

As a rule, the requirements under Article 3(3) are not applicable to either radio equipment or telecommunications terminal equipment, i.e. in the first place, radio equipment and telecommunications terminal equipment need not be so constructed that it:

- interworks via networks with other apparatus
- does not harm the network or its functioning nor misuse network resources
- incorporates safeguards to ensure that the personal data and privacy of the user and of the subscriber are protected, etc.

Only when the Commission decides that compliance with a requirement under Article 3(3) is necessary does this requirement become applicable. The Commission has, however, stated that it intends to apply these requirements sparingly and in justified cases only. The aim is for the market to regulate these aspects itself on a voluntary basis.

To simplify, it could be said that, currently, the R&TTE Directive only ensures that the use of radio equipment or telecommunications terminal equipment does not pose a threat to the life and limb of the user and that no excessive interference is caused to the radio spectrum.

Generally speaking, the new R&TTE Directive has considerably decreased the depth of regulation.

This means, for instance, that the application of harmonized standards does not automatically imply interoperability at or with a specific interface, unlike the interoperability guaranteed at the global system for mobile communication (GSM) or digital enhanced cordless telecommunications (DECT) air interface, for example, through application of the CTRs.

As a result, regulation loses its characteristic strength of ensuring the interworking of terminal equipment with its network. This is currently seen as a self-regulatory task of the market, with market players (manufacturers, network operators) themselves voluntarily agreeing and guaranteeing such interworking. Only time will tell how far this will succeed.

The R&TTE Directive introduced a new obligation for public telecommunications network operators, however, which will gain relevance when looking at the regulatory aspects of SDR later on. This obligation originates in Article 4(2):

Article 4

> Notification and Publication of Interface Specifications
>
> 2. Each Member State shall notify to the Commission the types of interface offered in that State by operators of public telecommunications networks. Member States shall ensure that such operators publish accurate and adequate technical specifications of such interfaces before services provided through those interfaces are made publicly available, and regularly publish any updated specifications. The specifications shall be in sufficient detail to permit the design of telecommunications terminal equipment capable of utilising all services provided through the corresponding interface. The specifications shall include, inter alia, all the information necessary to allow manufacturers to carry out, at their choice, the relevant tests for the essential requirements applicable to the telecommunications terminal equipment. Member States shall ensure that those specifications are made readily available by the operators.

This requirement is of interest when considering possible download scenarios for SDR, for instance, but we shall come back to this later.

10.2.1.2 Harmonized Standards

The Commission (after consultation with the Member States through the Telecommunication Conformity Assessment and Market Surveillance Committee, TCAM) issues mandates to ETSI, and to other European standardization bodies recognized by the EU, to develop documents for use as harmonized standards under the R&TTE Directive and covering specific essential requirements. The candidate harmonized standards are usually drawn up by ETSI using the same approval procedures as for a European Norm (EN) and are then forwarded to the Commission with a request for publication in the OJ. Once a candidate harmonized standard has been published in the OJ, it can be applied as a harmonized standard for assessing and declaring compliance with the essential requirements under the R&TTE Directive.

Manufacturers using a harmonized standard for declaring conformity with the essential requirements are always on the safe side because, as stated in Article 5(1), compliance with the essential requirements covered by the standard can then be presumed:

Article 5(1)

> 1. Where apparatus meets the relevant harmonised standards or parts thereof whose reference numbers have been published in the Official Journal of the European Communities, Member States shall presume compliance with those of the essential requirements referred to in Article 3 as are covered by the said harmonised standards or parts thereof.

However, each Member State has various options for intervening in cases where it does not believe that (radio) equipment complies with the essential requirements of the Directive, which for the sake of simplicity we shall not go into here.

10.2.1.3 Placing on the Market

Equipment meeting the essential requirements of the R&TTE Directive must not be required by Member States to comply with any additional provisions in respect of placing on the market. The simplest way for manufacturers to prove such compliance is to apply a harmonized standard, if available, which Member States will recognize.

> *Article 6*
>
> Placing on the market
>
> 1. Member States shall ensure that apparatus is placed on the market only if it complies with the appropriate essential requirements identified in Article 3 and the other relevant provisions of this Directive when it is properly installed and maintained and used for its intended purpose. It shall not be subject to further national provisions in respect of placing on the market.

Manufacturers, their authorized representatives established within the Community, or persons responsible for placing the equipment on the market who plan to bring on the market equipment using frequency bands whose use is not harmonized throughout Europe must follow the procedure in Article 6(4):

> 4. In the case of radio equipment using frequency bands whose use is not harmonised throughout the Community, the manufacturer or his authorised representative established within the Community or the person responsible for placing the equipment on the market shall notify the national authority responsible in the relevant Member State for spectrum management of the intention to place such equipment on its national market.

This notification shall be given no less than 4 weeks in advance of the start of placing on the market and shall provide information about the radio characteristics of the equipment (in particular frequency bands, channel spacing, type of modulation, and RF power) and the identification number of the notified body referred to in Annex IV or V.

If the manufacturer, authorized representative or person responsible for placing the equipment on the market does not receive a negative response from the competent national authority by the end of the 4 weeks, he may place his equipment on the market.

This would not have been possible under the old Terminal Directive regime. In the past, the formal consent of the national authority responsible in the relevant Member State for spectrum management was required in each and every case *prior* to placement on the market.

10.2.1.4 Putting into Service and Right to Connect

Diverging interpretations of Articles 7 and 8 of the R&TTE Directive among the EU Member States have led to discussions with the Commission.

> *Article 7*
>
> Putting into service and right to connect
>
> 1. Member States shall allow the putting into service of apparatus for its intended purpose where it complies with the appropriate essential requirements identified in Article 3 and the other relevant provisions of this Directive.
>
> *Article 8*
>
> Free movement of apparatus
>
> 1. Member States shall not prohibit, restrict or impede the placing on the market and putting into service in their territory of apparatus bearing the CE marking referred to in Annex VII, which indicates its conformity with all provisions of this Directive, including the conformity assessment procedures set out in Chapter II. […]

The Commission's essential objective behind the R&TTE Directive is to ensure the placing on the market and putting into service in the Member States of (radio) equipment which meets the essential requirements of the Directive.

The Member States and the Commission largely agree in respect of the placing on the market. However, the "putting into service in their territory of apparatus bearing the CE marking" has become the subject of discussion. In the case of equipment intended for frequency bands whose use is not harmonized throughout the Community, some Member States wish to reserve the right to lay down nationally applicable frequency usage conditions to supplement the conditions of the harmonized standards, where necessary in order to ensure national radio compatibility. Other countries regulate frequency usage through special licensing or approval procedures outside the scope of the R&TTE Directive. Frequency bands whose use is not harmonized throughout the Community are currently still the rule. Only the DECT[6] band and, to some extent, the GSM band have already been harmonized in a narrower sense.

10.2.1.5 Declaration of Conformity with the Essential Requirements

The mandatory procedure for declaring conformity with the essential requirements of Article 3 of the R&TTE Directive is described in Article 10 of the Directive:

> At the choice of the manufacturer, compliance of the apparatus with the essential requirements identified in Article 3(1)(a) and (b) may be demonstrated using the procedures specified in Directive 73/23/EEC and Directive 89/336/EEC respectively, where the apparatus is within the scope of those Directives, as an alternative to the procedures described below.
>
> Telecommunications terminal equipment which does not make use of the spectrum allocated to terrestrial/space radio communication and receiving parts of radio equipment must be subject to the procedures described in any one of Annexes II, IV or V of the Directive at the choice of the manufacturer.

Annex II, or 'Module A' (internal production control), describes the procedure whereby the manufacturer or his authorized representative established within the Community ensures and declares that the products concerned satisfy the requirements of the Directive that apply to them. The manufacturer or his authorized representative must affix the CE marking to each product and draw up a written declaration of conformity.

The manufacturer must establish the technical documentation required and he (or his authorized representative) must keep it for a period ending at least 10 years after the last product has been manufactured, available to the relevant national authorities of any Member State for inspection purposes. Where neither the manufacturer nor his authorized representative is established within the Community, the obligation to keep the technical documentation available is the responsibility of the person who places the product on the Community market.

The technical documentation must enable the conformity of the product with the essential requirements to be assessed. It must cover the design, manufacture, and operation of the product, in particular it must include:

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[6] The digital enhanced cordless telecommunications standard (www.dectweb.com).

- a general description of the product
- conceptual design and manufacturing drawings and schemes of components, sub-assemblies, circuits, etc.
- descriptions and explanations necessary for the understanding of said drawings and schemes and the operation of the product
- a list of the standards referred to in Article 5, applied in full or in part, and descriptions and explanations of the solutions adopted to meet the essential requirements of the Directive where such standards referred to in Article 5 have not been applied or do not exist
- results of design calculations made, examinations carried out, etc.
- test reports

The manufacturer or his authorized representative must keep a copy of the declaration of conformity with the technical documentation.

Where a manufacturer has applied the harmonized standards referred to in Article 5(1), *radio equipment not within the scope of Article 10(3)* is subject to the procedures described in any one of Annexes III, IV or V of the Directive at the choice of the manufacturer.

Annex III (Internal production control plus specific apparatus tests)[7] consists of the procedure laid down in Annex II plus the following supplementary requirements:

> For each type of apparatus, all essential radio test suites must be carried out by the manufacturer or on his behalf. The identification of the test suites that are considered to be essential is the responsibility of a notified body chosen by the manufacturer except where the test suites are defined in the harmonised standards. The notified body must take due account of previous decisions made by notified bodies acting together.
>
> The manufacturer or his authorised representative established within the Community or the person responsible for placing the apparatus on the market must declare that these tests have been carried out and that the apparatus complies with the essential requirements and must affix the notified body's identification number during the manufacturing process.
>
> Where a manufacturer has not applied or has only applied in part the harmonised standards referred to in Article 5(1), radio equipment not within the scope of Article 10(3) is subject to the procedures described in either of Annexes IV or V at the choice of the manufacturer.

Annex IV (Technical construction file) consists of Annex III plus the following supplementary requirements:

> The technical documentation described in Annex II and the declaration of conformity to specific radio test suites described in Annex III must form a technical construction file.
>
> The manufacturer, his authorised representative established within the Community or the person responsible for placing the apparatus on the market, must present the file to one or more notified bodies, each of the notified bodies must be informed of others who have received the file.
>
> The notified body must review the file and if it is considered that it has not been properly demonstrated that the requirements of the Directive have been met, the notified body may issue an opinion to the manufacturer, his representative or the person responsible for placing the apparatus on the market and must inform the other notified bodies who have received the file

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[7] Annex based on Module A with additional requirements appropriate to the sector.

> accordingly. Such an opinion must be given within four weeks of receipt of the file by the notified body. On receipt of this opinion, or after the end of the four-week period, the apparatus may be placed on the market, without prejudice to Article 6(4) (placing on the market) or Article 9(5) (safeguards).

Records and correspondence relating to the conformity assessment procedures must be in an official language of the Member State where the procedure will be carried out, or in a language accepted by the notified body involved.

Annex V (Full quality assurance) describes the procedure for manufacturers whose quality system for design, manufacture, and final product inspection and testing has been assessed and approved by a notified body and who can therefore carry out the conformity assessment procedure themselves.

10.2.2 Key Differences to the TTE Regime (Type Approval System)

A manufacturer's declaration of conformity with the essential requirements of the R&TTE Directive is sufficient for placing equipment on the market, subject to certain conditions (such as availability of a harmonized standard and a harmonized frequency band in the case of radio equipment).

The manufacturer need not necessarily involve a notified body. If he does so, he may even go against the opinion of the notified body and place a product on the market at his own risk.

The manufacturer himself decides which documents/specifications to use for declaring conformity with the essential requirements. The use of harmonized standards is not mandatory (unlike the application of CTRs).

Mandatory CTRs have therefore been replaced by voluntary harmonized standards.

If a manufacturer's product uses a frequency band the use of which is not harmonized, he must notify the national authority in the country where he intends to place the equipment on the market. The national authority then has 4 weeks to state whether or not the equipment may be placed on the market in its country. If the manufacturer does not hear from the authority by the end of the 4 weeks, he may place his equipment on the market in the relevant country.

The national authority may restrict the *putting into service* of radio equipment *only* for reasons related to the effective and appropriate use of the radio spectrum, avoidance of harmful interference or matters relating to public health.

According to Article 7(3) of the Directive, Member States must ensure that operators of public telecommunications networks do not refuse to connect telecommunications terminal equipment to appropriate interfaces on technical grounds where the equipment complies with the applicable essential requirements of Article 3. This obligation for operators is very interesting in light of the fact that not harming the network or its functioning and not misusing network resources and thereby causing an unacceptable degradation of service (Article 3(3)(b)) no longer constitutes an essential requirement.

None of the essential requirements under Article 3(3) are generally mandatory.

10.3 Regulation of SDR

As described in the previous sections, prior to the entry into force of the R&TTE Directive radio systems in Europe were subject to type approval. Type approval tests covered a set of parameters, including working frequency, output power and spurious emissions, and functionality tests for specific services (e.g. call set up and clearing, non-interference to the public network, etc.). Under the previous regime, equipment required new approval if any of these parameters were changed.

As already mentioned, the R&TTE Directive has considerably simplified the procedure for manufacturers. In principle, manufacturers now need only declare the conformity of their products with the essential requirements of the Directive as applicable to the intended use in order to be able to place their products on the market.

This procedure is relatively unproblematic as far as equipment is concerned whose behavior is determined by its hardware. This still applies to the majority of equipment today, but is expected to change in the future. Unlike today's equipment, the characteristics of SDR equipment (area of use, operating frequency, modulation technique, protocol, output power, etc.) can be modified during normal operation by a change in the software.

This means that SDR equipment would be able to load via software all the transmission standards in its feasible operating range, for instance 100 MHz–3 GHz. Likewise, a user would be able to use software to modify the equipment himself (by downloading software from the Internet) or even delete the equipment's functionality (pressing the reset button would delete the functionality and also eliminate any proof in the case of interference).

This functionality of SDR equipment raises various questions.

- Who, for example, is responsible for conformity with the essential requirements and hence for issuing the declaration of conformity: the equipment manufacturer or the customer changing the software?
- Does the user have to issue a new declaration of conformity after a software change?
- If not, how is it possible to ensure compliance with the essential requirements by the equipment in its new mode?

On the other hand, the possibility of modifying equipment characteristics by changing the software makes terminal equipment considerably more flexible, which can indeed also be of benefit.

In this section we look in detail at the regulatory aspects of SDR under the R&TTE Directive.

10.3.1 New Issues arising with SDR

10.3.1.1 Who is Responsible for the Declaration of Conformity under the R&TTE Directive? The Manufacturer? The User who Changes the Software?

Specific essential requirements – such as the definition of the intended working frequencies, output power, and spurious emissions in other frequency bands – need to be fulfilled before radio equipment can be placed on the market and operated in a given frequency band. SDR equipment is designed such that it may be possible in the future to modify the operating parameters of equipment during operation by changing the software. Such a software change could conflict with the preconditions for placing the equipment on the market under the R&TTE Directive and for operating the equipment: the change could cause the equipment to switch to a different mode (e.g. from GSM to TETRA, involving a change of frequency band, output power, etc.), for which no declaration of conformity with the essential requirements has been issued. The question then would be how to approach conformity assessment under the R&TTE Directive.

- Should conformity assessment in accordance with the R&TTE Directive be permitted only for hardware and software in combination or also for hardware and software separately? Should a distinction be made between radio equipment and wired equipment?
- Are the current provisions of the R&TTE Directive appropriate and adequate for SDR equipment? Should perhaps the requirements under Article 3(3) be made applicable to SDR equipment?
- How should the compliance of SDR equipment with the provisions be verified?
- Should there be regulations specifying who should change the software and how the software should be changed?
- Which means should be permitted for downloading new software – only interfaces authorized for such purposes and provided by, for example, the manufacturer, network operator, or service provider? To what extent should the software interfaces be standardized?
- Should measures to prevent manipulation or other security features be made mandatory? How should such security features function?
- Should additional requirements be set for SDR equipment in order to ensure the integrity of users' communications?

There are many questions for which, in Europe, no clear and harmonized answers have yet been determined, but which we will attempt to analyze.

It is unlikely that the user can be made responsible for compliance with the essential requirements because he cannot be expected to be familiar with all the legal aspects. If such highly flexible equipment is to be allowed onto the market, mechanisms are needed which ensure that the software available causes the hardware to operate only in those modes which are defined for the software and hardware in combination for the intended purpose and for which conformity with the essential requirements is ensured. This approach should apply at least to equipment using the radio spectrum, and is naturally dependent on various factors.

10.3.1.2 Which Parts of the Function of the Terminal should be Permitted to be Modified through a Software Change?

The first question to be answered is which equipment functions the software should be allowed to change. Let us look, for example, at loading new games onto radio equipment. If the games had a defined area for storing the software which was not connected to the operating system and ruled out a change of operating mode, then such a software change would certainly not be critical in terms of compliance with the essential requirements under the R&TTE Directive. Other software changes which could be viewed as uncritical are, for instance, those involving input field or key functions and also the installation of new services not affecting the radio equipment's operating characteristics (e.g. short message service (SMS) picture service).

One possible way to ensure that the operating characteristics are not affected is to allow users to make updates using only software or public interfaces authorized by the equipment manufacturer. The radio equipment could, for instance, be designed to check that new software is signed by the manufacturer and to reject any unauthorized software. This should apply to all software changes which could directly affect the equipment's mode of operation.

It therefore seems to make sense to have a separation between different software areas in the equipment, for instance areas which can be modified by the:

- equipment manufacturer only, e.g. mode (DECT, GSM, IMT-2000), frequency band
- network operator only, e.g. access to specific services and interfaces
- service provider only, e.g. software supporting specific service offerings
- user only, e.g. new games

The responsibilities for the various software areas should be clearly defined. Most importantly, the areas should be independent of each other, otherwise it could not be guaranteed that a change in one area would not lead to a change in another. This would make it difficult, if not impossible, to guarantee a separation of responsibilities and hence conformity assessment. This could ultimately mean that such radio equipment could not be placed on the market.

Let us assume the following.

Based on the essential requirements currently applicable, i.e. those in Article 3(1) (protection of the health and safety of the user, and EMC requirements) and Article 3(2) (effective use of the spectrum), a declaration of conformity from the manufacturer could be adequate for conformity assessment under the R&TTE Directive and for placing the radio equipment on the market, on one condition: the manufacturer must be able to guarantee that the software areas designed for the network operator, service provider, and user function independently of his area and cannot influence his operating system (DECT, GSM, IMT-2000, etc.).

The next question, however, is whether the current essential requirements are adequate for SDR equipment or whether it would make sense to supplement them by the additional requirements under Article 3(3).

Let us take another look at these additional requirements:

(a) *it interworks via networks with other apparatus and that it can be connected to interfaces of the appropriate type throughout the Community; and/or that*

This requirement would be of importance if we wanted to guarantee that only specific interfaces could be used for downloading software and hence signed software authorized for the specific radio equipment and available from those specific interfaces only could be downloaded.

(b) *it does not harm the network or its functioning nor misuse network resources, thereby causing an unacceptable degradation of service; and/or that*

It is quite conceivable that highly flexible radio equipment using incorrect or unauthorized software could cause interference to an operator's network or use network resources against the operator's will. At the moment it is difficult to say whether or not the network operator would be solely responsible for protecting himself against such cases of misuse or attack. A software update might, for instance, result in a protocol error in radio equipment, making it impossible for the equipment to establish a connection in a universal mobile telecommunications service (UMTS) system. The equipment would repeatedly try to set up a connection, with no success, and would unnecessarily occupy network resources.

It could therefore make sense, for example, for the equipment to carry out a self-check after each software update and to switch itself off or reverse the software change if it identified an error.

(c) *it incorporates safeguards to ensure that the personal data and privacy of the user and of the subscriber are protected; and/or that*

It is also quite conceivable that a network operator or service provider could read the telephone directories or other data (e.g. favorite Internet links) stored in radio equipment or that one service provider could overwrite another provider's data stored in equipment without the equipment user knowing. This means that without appropriate safeguards confidential data could be read, misused, or manipulated by unauthorized persons. Encrypting the radio interface could make sense in order to avoid unauthorized access.

(d) *it supports certain features ensuring avoidance of fraud; and/or that*

It should not be possible for the radio equipment to present a false identity to the network and hence provide scope for fraud.

(e) *it supports certain features ensuring access to emergency services; and/or that*

These could include the implementation of location-based services for emergency purposes, facilitating the location of persons making emergency calls and requiring assistance.

(f) *it supports certain features in order to facilitate its use by users with a disability.*

The examples given are just some of many feasible scenarios which can be used to analyze the essential requirements. The extent to which SDR equipment will really be subject to the requirements in Article 3(3) is a question which will require broad discussion among the public and in TCAM before it can be answered.

10.3.1.3 What should be Allowed to be Changed without the Users/Owners Permission?

In principle, we could say that no changes to the equipment software should be carried out without the user's/owner's permission. In practice, however, this could lead to difficulties because, for example, if it is a matter of improving the operating system software, the user/owner would probably not have enough technical understanding to assess the software changes. On the other hand, he should give his express agreement if, for example, a newly loaded service feature results in higher costs during use or if personal data are read out. Guaranteeing an appropriate duty of information, e.g. on the part of the manufacturer, network operator, or service provider *vis-à-vis* the users/owners could be a task for the regulator.

10.3.1.4 Software Download (e.g. Security Aspects)

The security aspects are one of the central points concerned with the introduction and use of SDR. How is it ensured that software can be downloaded and run only from interfaces intended for this purpose or that only software intended for the radio equipment can be downloaded and run? Would it make sense to agree on uniform standards for the relevant download interfaces? Should these interfaces and the authentication be prescribed in order to ensure that the SDR equipment can be used only with software in the assigned frequency ranges and that the radio equipment has a digital serial number to identify the manufacturer of the equipment and a signature on the software by the relevant providers (e.g. network operator, service provider, application software provider, etc.)?

Let us once again remember the requirements of Article 4.2 of the R&TTE Directive. This requires the public network operator to reveal its public interfaces and to describe them so precisely that a manufacturer can develop a piece of equipment for these interfaces and the services to be maintained over them. If no standardized interfaces are used for downloading software here in the SDR sphere, the effort to support the various interfaces with all their possible security requirements can be extremely high for the network operator and the manufacturer and thus unnecessarily expensive.

It would also be sensible to have an instrument with which we could prevent unauthorized software changes that could have an impact on the correct operation of a radio terminal. The ETSI, for example, is currently working on the development of a software download protocol that includes authentication and that uses the technology of the public code for encryption and digital signatures mechanisms. The extent to which a protocol of this kind is a solution to the outstanding questions is not yet known. However, other groups, such as the SDR Forum, are also in the process of developing standards for encryption and digital signatures. It would still be too early to propose specific requirements for authentication while the standards are still at the development stage.

It could make sense for the manufacturers of SDR equipment to take steps on their own initiative in order to ensure that only software that is part of a conformity declaration with a certain piece of hardware can be loaded into radio equipment. The software should not be able to allow the user to operate the radio equipment with a frequency, output power, modulation type, or other parameters not covered by the conformity declaration. Here, too, the question is posed as to how far the regulator should make proposals in this field.

10.3.1.5 Multiple uses of Frequency Bands by one Terminal

As an SDR terminal is easy to reprogram it would not be limited to being operated within a single fixed frequency range or only for a limited number of preprogrammed channels. It could be arranged so that it can work on every frequency that its design allows and it could be operated on channels of varying bandwidth with varying modulation formats. Furthermore, it should be possible to give the facilities some ‘intelligence’ so that they monitor use by third parties in the spectrum and could transmit on free frequencies. These abilities could open up new possibilities in the field of frequency assignment and licensing. Instead of relying on a user finding a free frequency prior to transmission in a somewhat overloaded frequency range, a radio terminal could monitor a broad range of frequencies and find a free range with sufficient bandwidth in which the user can become active.

The use of SDR can also enable new types of joint frequency use not yet allowed by today’s conventional equipment. If a mobile radiocommunications licensee has more frequencies than he directly needs, he could rent these frequencies to third parties at short notice. A SDR would facilitate such joint use. For example, a third party could acquire SDR terminals from a manufacturer that can be configured in such a way that different services can be offered in various frequency ranges. Once the frequency usage conditions have been negotiated the third party could rent a ‘package’ comprising equipment and ‘transmission time’ to end users who need communications capacity at short notice. He would load the software required to configure the equipment correctly when the end user enters into the rental contract. An alternative for the end user would be to contact the licensee directly with respect to the frequencies needed and then rent the correctly configured SDR terminals. With today’s technology such a joint use at short notice is very difficult, or impossible, to arrange because of the difficulties resulting from the quick configuration of radio equipment for various applications in new types of frequency configurations. The advantages for the public may be that there would be more communications capacity for the end user and that the spectrum could be better used as a resource.

In a slightly modified shared use scenario, the owner of a license for a frequency block that is not being fully utilized could negotiate with a second party about approval for use of part of the spectrum at times when this part of the spectrum is available. The licensee could use an organization channel to ensure that he primarily has access to the spectrum. In the case of a system of this kind, for example, the primary user of a signal would be transferred within the organization channel as soon as the frequency range was available for use by the second user. The second user's transmitters would have to check whether the signal is constantly present in the organization channel and they would have to cease use of the frequency block immediately when the signal disappears from the organization channel. These checking/stopping capabilities in the SDR terminals would guarantee the primary user quick and reliable access to the spectrum when he needs it. There are therefore 'no interruptions' in the jointly used spectrum. Frequencies that may not be constantly available are not suitable for some applications but they may be of interest for those applications where the user is prepared to accept a less reliable service for less money and for data applications for which there are alternative transmission possibilities.

Functions such as those described in the paragraphs above could allow a more effective use of the spectrum. However, given the current legal framework in the EU, such a flexible use of the spectrum is scarcely possible for use in the Member States.

10.3.1.6 Influence on Emergency Services and Mobile Services?

The fact that various emergency services use different technical standards as a transmission medium that are not interoperable (e.g. they use the same frequency band but different transmission protocols or use different frequency bands and different transmission protocols) can be a serious problem. For example, it may be the case that different public security services (e.g. ambulances, police) that react to an emergency call cannot communicate with each other because they have no means of working on the frequency of their counterpart. This is where the SDR technology could play a special role and the regulator could pay particular attention to this.

The lack of common transmission standards or the existence of several transmission standards can also cause problems for commercial mobile radiocommunications services. For example, it is possible that a mobile designed for operation in a specific mobile communications system cannot be used in another mobile communications system based on different technology. If, in addition, the operator of a mobile communications system wants to change to a different transmission system, he has to exchange all base station transmitters and mobile units. This can be a complicated and expensive process. The possibility that SDR terminals can change frequency and transmission standards seems to be a way of bridging the lack of interoperability between different mobile communications systems. It remains to be seen how far this can be achieved in the future.

10.3.1.7 Electronic Marking of the Equipment?

A key part of putting radio terminals into circulation is the correct CE marking of the terminal. For example, all of the currently required information with respect to CE marking could be made visible with a liquid crystal display (LCD), as a result of which there would be no need to re-mark the terminal in the event of a change to the software because the CE mark could be adjusted with the software update. As already mentioned, a distinction should be made between a software update with an influence on the radio parameters of a radio terminal and a software update that changes only certain functions of the terminal. In this case, depending on the change made, a change in the marking could be waived.

10.3.1.8 Signature of Software? History Documentation?

The software that may be used in a SDR could, for example, be signed by the manufacturer of the radio terminal and thus released by him for use in his radio terminal. This would guarantee that the radio terminal would meet the applicable technical requirements under all operating conditions. In order to ensure that software that has not been released cannot be downloaded, these radio terminals would have an authorization system that checks the software for an authorization code, which, for example, is added by the manufacturer, network operator, or the national administration.

It may be necessary to specify methods that allow the user to note whether the desired operating software is currently loaded in a SDR terminal and that allow the market monitoring authorities of the Member States to check whether the software complies with the regulations in force.

The question is whether such a procedure is needed, enforceable, and practicable. What type of authentication system should be used? Should it be a single system or should there be alternative systems? Who should be responsible for generating the authentication code? The manufacturer of the equipment or a different body?

Do we need a method to show the information about the software loaded into a SDR? If yes, what method should be used and what information should be shown? It could make sense to have a history of all the software ever loaded onto the terminal, for example, so that subsequently, in the event of possible faults there would be the possibility of finding a cause. Otherwise, the person causing the fault could simply delete his software in his terminal and nothing could be proved.

On the other hand, one can argue that there may be definite parallels between a SDR and a PC connected to the Internet via a public network. What form does regulation take there at the moment? The user can download any software from the Internet. This software can change his entire operating system, open up new services to him without the regulator intervening. The user himself is responsible for no personal data being read out of his computer by, for example, installing a firewall on his PC. If he uses his credit card to pay bills over the Internet, he does so at his own risk. Does this mean that no special regulations are needed for SDR? The answer to this is not easy at all.

10.3.2 Development of Common European Regulations

10.3.2.1 Unlike the US, Europe is a Collection of Nation States, each with their Own Regulatory Bodies

Each nation state in Europe has its own tradition in dealing with security issues and regulation in telecommunications. European directives, such as the R&TTE Directive, are gradually leading to a common understanding of regulation in telecoms. Thanks to their possible flexibility, SDR terminals also need to be examined closely by the regulator. Since Europe has set itself the goal of a single market it is sensible to enter into a discussion between the Member States about the possible regulatory aspects of SDR. For example, this can be achieved by means of relevant workshops at the Commission or in Member States, the Electronics Communications Committee (ECC) or by means of discussions in TCAM.

10.3.2.2 The Process of Consultation – National and Europe-wide

A discussion about the development and introduction of SDR terminals has now started in some, if not all, Member States. National research projects are delivering the first technical feasibility scenarios. The Commission, too, has commissioned and is commissioning research projects in the field of SDR. Some Member States are also planning public hearings on this subject in the near future. In this way, the picture of the probable amount of regulation required will be completed and a good foundation for discussion will be obtained.

10.3.2.3 The Role of TCAM in the Process

As Europe is interested in a market that is as uniform as possible and it is also the declared goal of the Commission to achieve this, consensus must be achieved between the Member States, if possible, about the depth of regulation for SDR. For this reason, special importance is attached to TCAM. All the Member States of the EU are represented in this committee. As a result, TCAM is an appropriate discussion platform. Moreover, this committee issues relevant recommendations to the Commission about the depth of regulation. The Commission then ultimately decides on the application of Article 3.3 requirements.

10.3.2.4 Likely Approaches and Time Scales to Developing a Common Position

In the next 2 years European research projects in the remit of the Commission will be completed that also deal with regulatory aspects of SDR systems. Furthermore, national consultation processes will take place. The next 3–4 years will be decisive for specifying the regulatory framework of SDR.

10.4 Conclusions

In future, SDR terminals will need a very flexible regulatory approach if we want it to be able to develop its full potential. In this connection, the regulator should carefully weigh up the interests of the user/owner of the SDR terminal against the interests of the manufacturers, network operators, service providers, and application providers. This will not be possible without a correspondingly broad discussion with the affected groups. Special attention will probably have to be paid to all aspects of security. In order to prevent an unnecessary delay in the introduction of SDR the interested groups should address the regulators (national and the Commission) at an early stage in order to set in motion all of the necessary processes.

Further Reading

[1] Cook, Peter G. and Bonser, Wayne, ‘Architectural overview of the SPEAKeasy system’, *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 4, April 1999.

[2] EC Council Resolution of May 7, 1985 ‘On a new approach to technical harmonisation and standards’.

[3] EC Council Directive 91/263/EEC ‘On the approximation of the laws of the Member States concerning telecommunications terminal equipment, including the mutual recognition of their conformity’.
[4] ‘Statement of Intent on Common Technical Regulations’ Doc Temp TRAC (91-15)3.
[5] EC Council Directive 93/97/EEC ‘Supplementing Directive 91/263/EEC in respect of satellite earth station equipment’.
[6] EC Council Directive 93/68/EEC ‘Amending Directives 91/263/EEC (telecommunications terminal equipment), and 73/23/EEC (electrical equipment designed for use within certain voltage limits)’.
[7] EC Council Directive 93/97/EEC ‘Supplementing Directive 91/263/EEC in respect of satellite earth station equipment’.
[8] ETSI rules for TBRs.
[9] Directive 1999/5/EC of the European Parliament and of the Council of March 9, 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity.
[10] ETSI EG 201 399 V1.1.1 (2000–01) ‘A guide to the production of Harmonized standards for application under the R&TTE Directive’.
[11] Federal Communications Commission: Inquiry Regarding Software Defined Radios ET Docket No. 00-47 (adopted: March 17, 2000; released: March 21, 2000).
[12] TRAC Handbook on CTRs, June 1996, Issue S.

11

Regulation of Software Defined Radio – United States

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More than any other regulatory body in the world, the US Federal Communications Commission (FCC) has recognized the potential of software defined radio (SDR) and worked to create a regulatory environment in which SDR can thrive. The FCC has diligently examined the specific regulatory challenges that SDR faces, mainly in the area of handheld equipment authorization, and has made a point of re-examining certain regulations that might unnecessarily hinder SDR's development and deployment. And although the FCC has been, and remains, extremely bullish on the long-term prospects for SDR, it has been careful not to get ahead of industry in its thinking or in its predictions for SDR's implementation.

11.1 Early Contacts

Commission staff have been aware of SDR since its emergence in the mid-1990s, but its involvement really began in earnest when Dale Hatfield began his term as Chief of the FCC's Office of Engineering and Technology (OET) in 1999. Mr Hatfield had been vaguely aware of SDR in the mid-1990s, but did not focus on SDR until coming to OET. In fact, one of the very first e-mails he received as OET Chief in early 1999 was from a respected senior engineer at the FCC's laboratory advising him to focus on the potential of SDRs. Mr Hatfield later recounted how much this e-mail piqued his interest in the topic – an interest that he maintained throughout his service at OET.

Software defined radio is a natural fit with OET's duties and responsibilities, making clear why that office has always spearheaded the FCC's approach to SDR. Among other duties, OET provides technical advice to other bureaus and offices and to the Chairman and other Commissioners. It administers FCC rules dealing with spectrum allocation, experimental licenses, unlicensed devices, and certain industrial, scientific, and medical equipment. Finally, OET oversees the Commission's equipment-authorization program, including the work that is done at the FCC's laboratory facilities in Laurel, Maryland.

Each of these responsibilities is relevant to SDR's emergence. OET began closely following SDR developments because of its responsibility to stay abreast of major technological developments, and to advise the other bureaus and offices and the Commissioners about those developments. But it has since become interested in SDR's potential to allow interoperability between and among different radio services and systems, and more recently has examined whether SDR can aid in the development of secondary markets for spectrum. Similarly, OET's spectrum-allocation role requires it to stay on top of advances in the capabilities of telecommunications equipment. In this regard, OET has been interested in how SDR technology could, among other things, promote more efficient use of spectrum through innovative sharing arrangements.

The OET's final principal responsibility – equipment authorization – has been by far the largest focus of the notice of inquiry and rulemaking proceedings that are discussed in detail below. The OET has been working with industry for years to determine how to streamline the equipment-authorization process in ways that would enable faster introduction of SDR capabilities.

11.2 The Notice of Inquiry

In March 2000, the FCC released an OET-drafted Notice of Inquiry (NOI) on SDR[1]. The SDR NOI recognized the tremendous possible benefits of SDR to users, including a greater variety of features and the ability to adapt to multiple communications standards. Likewise, the NOI identified potential efficiencies for manufacturers, such as increased economies of scale, increased opportunities for worldwide marketing of devices, and a decrease in the number of devices that would need to be manufactured and maintained in inventory. And the Commission rightly focused on SDR's potential to greatly improve the efficiency of spectrum usage, and to overcome the incompatibilities that have developed between various communications services, both in the US and internationally.

To further these goals, the NOI requested comments from the public on four general aspects of SDR technology:

- *The status of SDR technology*. The Commission sought input on a broad range of factors, including the features of a radio device that are likely to be controlled by software, the specific limitations and cost implications of SDR technology, the ways in which SDR performance might exceed the capabilities of non-SDRs, the likely timeline for SDR implementation, and the prospects for international cooperation to advance SDR technology.
- *Interoperability*. Noting the inability of many users to communicate over different standards between services – or even within services – the Commission posed a series of questions about SDR's ability to improve interoperability across differing transmission standards, particularly in the context of public-safety agencies attempting to coordinate responses to emergency situations.
- *Improving spectrum efficiency and spectrum sharing*. The Commission noted that the

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[1] Notice of Inquiry, In re Inquiry Regarding Software Defined Radios, ET Docket No. 00-47 (rel. March 21, 2000) ('NOI' or 'SDR NOI'). The Commission uses the Notice of Inquiry (NOI) procedure – as opposed to the more common Notice of Proposed Rulemaking (NPRM) – when it wants to gather information about a telecommunications-related topic but is not yet prepared to propose specific new rules relating to that topic.

reprogrammability of a SDR device could allow the device to operate on various frequencies, on channels of varying widths and with varying modulation formats. In the longer term, the Commission expressed optimism about the possibility of 'smart' devices seeking out unutilized spectrum, and innovative sharing arrangements that would enable spectrum leasing. The Commission posed a broad-ranging series of questions in this area, focusing on how SDR may achieve better spectrum efficiency and what the FCC might do to permit SDR to enable things such as spectrum-sharing arrangements.

- *Equipment approvals*. Noting that existing rules did not allow devices to be modified without going through a new full authorization application, the Commission asked whether SDR would benefit from streamlined rules allowing modifications to occur in the field, without new authorization and labeling requirements. In this regard, the Commission also inquired about what security and authentication measures might be required to ensure that SDR downloads do not result in unauthorized operations and/or interfere with other licensed users of the spectrum.

The FCC invited interested parties to file comments on the SDR NOI in June 2000, with reply comments following a month later. More than 20 parties filed comments, including handset manufacturers, wireless operators, public-safety agencies, the US government's spectrum manager, and others with an interest in wireless technology or spectrum management. The comments, and the FCC conclusions that followed,[2] are best summarized in the context of the FCC's four areas of inquiry.

11.2.1 The State of SDR Technology

Based upon the comments, the FCC quite correctly concluded that most features in a radio could eventually be controlled by software (NPRM para. 9). The comments of the SDR Forum – an open, non-profit corporation dedicated to supporting the development and deployment of flexible, adaptable architectures in advanced wireless systems – noted that software could eventually control virtually any RF attribute. Table 11.1, prepared by the SDR Forum, illustrates the likely progression of *commercial* radio functions; some techniques are further advanced in the defense community. Column I indicates functions that, as a practical matter, can only be implemented in hardware; Column II includes functions that can be controlled by software but must still include a hardware component; Column III denotes functions that can be run entirely by firmware (software that is not designed to be altered after manufacture); and Column IV lists functions that can be run by post-manufacture, reprogrammable hardware and software – the real spirit of SDR in that it is changeable after shipping.

Based on this and other submissions, the Commission determined that SDR is already in widespread use in base stations and will be similarly widespread in handsets within 5 years, despite current limitations that must be overcome with respect to cost, complexity, size, and the speed of the circuitry (NPRM para. 11).

The NOI comments also described several capabilities that are not present in current radios, including post-manufacture reprogrammability and common hardware platforms

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[2] The FCC responded to the NOI comments in its December 2000 NPRM on SDR. See Notice of Proposed Rulemaking, In re Authorization and Use of Software Defined Radios, ET Docket No. 00-47 (rel. December 8, 2000) ('NPRM' or 'SDR NPRM').

Table 11.1 The likely progression of commercial radio functions

	Fixed hardware	Software-controlled hardware	Firmware	Post-manufacture reprogrammable hardware/software
Today	• Antenna	• Frequency (VCO) • Baseband bandwidth • Output power • Modulator (switched) • Encryption/security • RF selectivity • IF conversion • Chip rate processing	• Frequency (digital synthesis) • Modulation (digital synthesis) • Encryption/security • Smart antenna signal processing • Source coding/decoding • IF selectivity • Power system management • Symbol rate processing • Frequency conversion	• User interface
Near term		• Smart antenna	• [Items above] • Chip rate processing (2G, 3G)	• [Items above] • Provisioning of user terminals • Capabilities rules engine • Source coding/decoding • Chip rate processing (2G, 3G) • Symbol rate processing (2G, 3G) • Smart antenna signal processing • Encryption/security • Applications signal processing (e.g. audio, video, security)
Longer term		Smart antenna	RF front end	• [Items above] • Frequency (digital synthesis) • Modulation (digital synthesis) • Advanced smart antenna signal processing • IF selectivity • Battery system power management • Frequency conversion • Adaptive radio access (e.g. cellular, fixed wireless, Bluetooth)

for manufacturers. In base stations, the Commission noted the promise of reduced size and enhanced technical flexibility at lower prices than base stations employing a separate transceiver for each radio frequency carrier (id. para. 11).

11.2.2 SDR and Interoperability

As the FCC expected, the comments on interoperability generally agreed that SDR could help improve interoperability between public safety agencies as well as in commercial radio services, but not in the immediate future (id. paras. 12–13). The comments generally agreed that several issues must be resolved before roaming between different standards on different networks can occur. These include protocols for handling traffic, channel-establishment procedures, authentication and fraud detection. Still, commenters as disparate as AirNet and the National Telecommunications and Information Administration (NTIA) agreed that SDR could eventually facilitate interoperability in a number of ways, including multiple channel operations, translation, smart antennas that can operate over multiple bands, multiband power amplifiers, tunable preselectors, interference cancellers, low noise synthesizers, wideband low noise amplifiers and mixers, high throughput digital signal processors (DSPs), and smaller chip packaging (id.).

11.2.3 SDR and Spectrum Efficiency

Although most of the NOI comments agreed that SDR is likely to improve the efficiency of spectrum use in the long run, a number of parties expressed concern that the spectrum-efficiency benefits of SDRs are not yet technically or commercially feasible and no regulatory changes should take place at this time (id. para. 14). A minority of commenters suggested changes to the way the Commission currently allocates or licenses spectrum to allow greater spectrum sharing through greater flexibility and secondary use, but most advocated no changes should be made to the spectrum allocation rules and cautioned the Commission that SDR is not a near-term replacement for conventional spectrum management (id.).

11.2.4 Authorization of SDR Equipment

As noted above, the NOI sought comments on several issues related to authorization of SDR equipment, including the approval of radio hardware and/or software; the required compliance measurements; the authorization process; the regulation of software changes; and the need for requirements to prevent unauthorized modifications to equipment (NOI para. 19). A number of commenters argued that the intended combinations of SDR software and hardware should be approved jointly (NPRM para. 16). The SDR Forum, for example, took the position that each possible combination of hardware and software that a radio will support should be tested in the same fashion that single-mode systems are tested today (id. para. 16, n. 30). NTIA noted that SDR technology had not matured to the point where it is possible to predict radio RF parameters from examining only the software or hardware, and that separate hardware or software approval would have to wait for a consistent predictable connection between the software and hardware (id.).

At the same time, several parties suggested SDR-related changes to the Commission's equipment-authorization procedures (id. para. 17). There was general consensus that the

Commission's current equipment authorization procedures could be overly burdensome and could limit the enhanced flexibility that SDR might otherwise provide. A number of parties also recommended either manufacturer's self-approval for SDR, or certification by independent telecommunications certification bodies (TCBs), in addition to FCC certification.

Many parties, led by the SDR Forum, proposed an amendment to the requirement that a device display its FCC ID number via a label affixed to the device's surface (id. paras. 17, 29). These parties suggested that all information currently required to be displayed on the FCC label could be made available on a liquid crystal display (LCD) or light emitting diode (LED) display, which would eliminate the need to relabel equipment in the field when the software is changed (id.). Other parties suggested rules to distinguish between software that can affect the device's RF emissions from software that cannot, and allow the latter type of software to be downloaded without relabeling or re-certification of any kind.

11.3 Initial Conclusions – The Notice of Proposed Rulemaking

In light of the NOI responses, the Commission tentatively concluded that it would be premature to proceed with specific rule proposals on interoperability or spectrum efficiency. Instead, the Commission has proposed to continue monitoring developments in these areas as the technology develops (id. paras. 13, 15).

Having decided that rule changes based on SDR's interoperability or spectrum-efficiency capabilities would be premature, the FCC released a December 2000 NPRM on SDR that was almost entirely devoted to equipment-authorization issues. It proposed both to streamline certain authorization procedures and also to establish certain security and authentication safeguards to ensure the reliable operation of SDR equipment.

As a preliminary matter, the Commission tentatively concluded that radio hardware and software should be approved together (id. para. 18). In the Commission's view, this was the only way to prevent interference, protect users from excessive RF radiation, and ensure that equipment complies with the Commission's technical standards (id.). The NPRM further concluded that the Commission, rather than TCBs, should handle all SDR certification for the time being (id. para. 33).

Turning to the new rule proposals, the FCC first set out to define, for regulatory purposes, exactly what is a 'software defined radio':

> A software defined radio is a radio that includes a transmitter in which the operating parameters of the transmitter, including the frequency range, modulation type or maximum radiated or conducted output power can be altered by making a change in software without making any hardware changes (id. para. 21).

This definition is extremely important; devices that do not meet it cannot be certified as SDRs and therefore are not eligible for the streamlined equipment-authorization and labeling procedures outlined below (id. para. 26).

Second, the Commission proposed a new streamlined equipment approval process for SDRs. Under the current rules, any change to a transmitter's regulated operating parameters – operating frequencies, output power, or modulation type – requires a new authorization, including relabeling with a new FCC ID number. The only exceptions to this rule have been two classes of minor changes. 'Class I' changes are those that do not affect the transmitter's RF characteristics (see 47 C.F.R. Section 2.1043). 'Class II' changes, on the other hand, *do* affect RF characteristics, but in very minor ways that do not change the power, frequency, or modulation (id.). Neither of these classes can encompass the major post-manufacture changes of which SDRs will be capable.

To accommodate SDRs, the FCC has proposed adding a ‘Class III’ permissive change procedure to enable in-the-field modifications of SDR devices’ operating parameters (NPRM para. 24). The Class III proposal, however, is extremely narrow – permission could be granted only to the original equipment manufacturer, and only for devices that have never received hardware modifications (id. para. 26). To ensure that the efficiencies of software downloads are better realized, the NPRM tentatively concluded that a SDR can be equipped with an ‘electronic label’ that would display the device’s FCC ID number by means of a LED, LCD, or other similar display method (id. para. 29). The FCC envisions that electronic labeling will allow in-the-field relabeling if a new authorization is obtained by a third party for a previously approved device (id.).

Finally, on the issue of security and authentication, the NPRM proposed a wait-and-see approach, in line with the SDR Forum’s proposal that the Commission not cut short industry efforts to develop reliable security and authentication safeguards. Although the Commission concluded that any SDR manufacturer must take reasonable steps to prevent unauthorized software changes, it declined to propose specific rules governing security and authentication. Rather, the NPRM noted that the SDR Forum and the European Telecommunications Standards Institute (ETSI) are developing standards for encryption and digital signatures, and the Commission chose not to undercut those efforts by prematurely mandating particular standards (id. para. 31).

11.4 The First Report and Order on SDR

On September 13, 2001, the FCC adopted its *First Report and Order* on SDR at its monthly open meeting.[3] The *Report and Order* adopted the rule proposals laid out in the NPRM almost verbatim, and they will now be incorporated into Part 2 of the Commission’s rules, which govern frequency allocations, treaty matters, and general rules and regulations, including equipment-authorization rules.

The specific rule changes are straightforward. First, the regulatory definition of SDR is virtually unchanged from the NPRM text:

> *Software Defined Radio*. A radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power (either radiated or conducted) can be altered by making a change in software without making any changes to hardware components that affect the radio frequency emissions.

(First R&O para. 8 (to be incorporated into the Commission’s rules at 47 C.F.R. Section 2.1))

The only substantive change to the NPRM’s proposed definition is at the end: the NPRM’s reference to “hardware changes” has been replaced by a reference to “changes to hardware components that affect the radio frequency” (id.). The Commission’s intent appears to have

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[3] First Report & Order, In re Authorization and Use of Software Defined Radios, ET Docket No. 00-47 (rel. September 14, 2001) (‘First R&O’).

been to clarify that the installation of new memory modules or the use of software downloads to reconfigure existing hardware or firmware logic would be permitted under the definition (id.).

Second, the 'Class III' permissive change mechanism also follows the contours proposed in the NPRM. Specifically, 'Class III' changes are now possible for radios initially certified as SDRs, but they can only be obtained by the original grantee and only if the radio's hardware has not previously been changed in a way that affects the radio's frequency emissions.[4] The specific Class III rule changes are codified in Section 2.1043 of the Commission's rules (47 C.F.R. Section 2.1043).

Third, the Commission has decided that it will not impose specific SDR-related security requirements, instead putting the onus on SDR manufacturers to ensure the security and reliability of their devices (First R&O paras. 31–32; 47 C.F.R. Section 2.932(e)). This is not a final decision, however. The Commission will await further input from industry and from other government agencies over the next year before deciding whether to adopt more detailed security requirements (First R&O para. 32).

Fourth, the Commission adopted electronic labeling under the framework proposed in the NPRM (id. para. 35). Electronic labeling will be allowed via LED, LCD, or 'similar display device', and it will require only the display of the device's FCC identification number (id. para. 39).

Interestingly, in some respects, what is *not* in the *First Report and Order* is as significant as what is there. For example, the FCC rejected calls for SDR-specific enforcement capabilities (id. para. 48) finding that existing procedures should be adequate. And the FCC also rejected stringent limits on the number of hardware and software combinations that are possible under a single authorization, noting that such limits would hinder the development of common hardware platforms (id. para. 25). Likewise, the Commission has refused to require applicants to submit a copy of SDR software to the Commission along with any application (id. para. 27) (although the Commission retained the right to request such submissions under new 47 C.F.R. Section 2.944).

Finally, by labeling the order a 'first' report and order, the FCC has also indicated that this proceeding will remain open so that the Commission can more quickly respond to advances in SDR technology. The *First Report and Order* is almost certainly the first of many.

11.5 Conclusion

From the OET staff all the way up to the Commissioners themselves, the FCC has acted expeditiously to learn about SDR, enable its use in the US, study its potential benefits, and promote its acceptance to other regulators worldwide. This process will continue through what is anticipated to be a series of proceedings over the next several years that will further modify the FCC's rules and regulations to be responsive to the potential benefits of SDR.

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[4] Thus, a 'Class III' change can be made to a device that has already undergone a 'Class I' change, but not one that has received a 'Class II' change. A Class I change is one that does not degrade the device's reported radio emissions characteristics in any way (47 C.F.R. Section 2.1043(b)(1)). Class II changes are those that degrade the reported radio emissions characteristics, but not in a way that would violate the minimum requirements of any applicable FCC rules (id. Section 2.1043(b)(2)).

Part IV

Early Products

12

Defense: A Realized Software Defined Radio Family for Military Applications

Rainer Bott and Ruediger Leschhorn

Rohde & Schwarz

Software defined radios (SDRs) currently are under investigation and development for government and defense communications, as well as for commercial mobile telephony applications. In this chapter an example is given of a family of already realized SDRs whose versatility allows dual use, supporting military as well as civil waveforms.

In order to give the reader an understanding of the rationale and the design principles of the product family, a short introduction is initially provided to the requirements and peculiarities of defense applications. Starting out from these requirements, the underlying technology platform is described, which serves as the basis for the members of the radio family. After that the airborne radio M3AR, the tactical radio M3TR, and the stationary radio M3SR are in turn described, to illustrate the state of the art of SDRs for military communications. The chapter concludes with a brief summary and future outlook.

12.1 Peculiarities of Defense Applications of SDR

The requirements of military communications are influenced by the existence of several different key usage scenarios, such as:

- In peacetime, practice is necessary in order to maintain a high level of defense capability. This scenario incorporates an available, fully accessible infrastructure. The tasks to be performed are not critical to survival and the communication means are not very different from civil communication.
- Unfriendly environments, e.g. maneuvers, peacekeeping, and humanitarian operations, are characterized by worsened conditions regarding infrastructure. The communication often cannot rely on a given infrastructure. The military communication systems may have to provide their own networks. Environmental conditions are often harsher.

- In full conflict scenarios, establishing communication is very time critical and often is necessary for survival. Transmissions will be jammed. Rapidly changing scenarios give rise to the need to communicate with different partners at different times. The respective communication links can have different waveforms and protocols and also different frequency ranges. It may be necessary, for example, for a squad leader to communicate with his superiors via a platoon command net and with his team leaders via a squad net using the same radio at the same time. This scenario requires that the operation of the radio must be simple, to avoid incorrect action. The environmental conditions may be very harsh. As can be seen, the radio may need to operate as a multiband and multirole radio.

Consideration of the above scenarios demonstrates that military communications require high levels of:

- interoperability
- information security
- operational security
- logistics/integrated logistic support (ILS)

Whilst some of these requirements also arise in civil applications, the military application places a heavier stress on them.

12.1.1 Interoperability

As described above, the different tasks of modern armed forces go well beyond the classical defense scenarios. The radios used within all of these scenarios have to cope with standardized military waveforms for transmission security (TRANSEC, e.g. using frequency hopping) and/or communication security (COMSEC, e.g. using encryption). Those standard military waveforms like Have Quick and SATURN are necessary in order to allow interoperability with NATO partners.

Furthermore, non-NATO and even NATO partners sometimes prefer to be able to use their own dedicated waveforms for secure communication, e.g. the Rohde & Schwarz proprietary SECOS and SECOM waveforms, operating in the same or in different frequency ranges.

In a joint multinational activity, the different forces have to communicate with each other using common waveforms, but preserving the possibility for private communication within each armed force using proprietary waveforms.

In peacekeeping and humanitarian activities, there is the need for communication with the local authorities and civil organizations. Therefore, the forces also need to be able to access the domestic communication networks and radio communication standards (e.g. public switched telephone network (PSTN), global system for mobile communications (GSM), or TETRA (terrestrial trunked radio)).

Consequently, the SDR used for modern defense applications has to deal with a large number of different standards, both military and civil, which operate in different frequency ranges. The radio must be able to access multiple standard communication networks.

12.1.2 Information Security (InfoSec)

Military communication needs a very high level of information integrity regarding the identification of both sender and receiver, resistance against attacks, intrusions, and modifications of the contents. Communication must be secured against interception, using electronic protection measures like frequency hopping or spread spectrum techniques. Furthermore, using encryption techniques, the content can be protected against modification and eavesdropping. Net structures must be protected against being detected as well – low probability of interception (LPI).

Robust communication links in jammed environments are mandatory. Protocols need to be adaptable, to match demanded throughput while maintaining the robustness in different scenarios.

Military radios may be captured by hostile forces. Important information, such as cryptographic information, stored within the radio, needs a very high protection against being read out. Similarly, the use of the radio by the hostile forces, e.g. to listen into confidential communications, must be prevented.

Therefore, the SDR must provide functions like zeroizing (erasure of stored keys), expiration dates of keys and software modules, and highly sophisticated access restriction schemes, both for local and remote control.

While the information security at the air interface is taken into account by the waveform specification, information security within the physical radio itself is the task of the radio vendor.

In order to keep nomenclature consistent with company terms, in this chapter InfoSec is referred to as protection processing and the InfoSec unit itself is designated as the protection processor.

12.1.3 Operational Security

Regarding the operational scenarios, the operation of military radios must match different user levels. During mission planning, basic settings of the radios like selection of the communication standards to be used,[1] net settings according to the net and frequency planning and loading of the keys for secured communication are performed. During operation, it must be possible to control the radio via simple actions without the need to go through complex menu structures. Fail-safe operation is necessary – e.g. for inhibiting plain text transmissions when encryption and frequency hopping are required.

Many applications require remote control operation of the radio. The control functions of the radio need to be protected against unauthorized access. If such an access could take place, settings could be changed or even new software could be downloaded into a SDR, thus making it inoperable or insecure.

12.1.4 Logistics/ILS

Modern armed forces use a lot of radio communication equipment to support different scenarios, protocols, frequency ranges, etc. Therefore, logistics and repair concepts are

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[1] The setting/selection of the communication standard may include the software download of the waveform.

important factors for maintaining radio communication in defense scenarios. Due to the extreme life cycle of military standards, availability of the radios for at least 10 years and the possibility for repairing them for at least 15 years are still today mandatory. Consequently, a radio vendor needs to provide ILS for its radios.

Software defined radios can help the armed forces to simplify the logistical concepts. By using identical hardware provided by a dedicated vendor for different applications of its radios, replacement of defective parts is made easier.

Because of the very harsh operational environment, the probability of damage and failure is high, even though the radio is especially designed to face this environment. In order to meet low meantime to repair, module replacement is typically done in the field, whilst repair of modules is done in the workshops of the armed forces or of the vendor. Due to the incarnation of the functions in software, the SDR is basically a computer, which runs different communication standards. Therefore, location and repair of defective modules does normally not need highly sophisticated analog measurement instruments, but instead relies on sophisticated test software and built-in-test functions.

12.2 The M3xR Technology Platform

The radios of the M3xR family are based on the same technology platform, using identical processor families for the different tasks within the radio, e.g. human–machine interface (HMI) and radio control, digital signal processing, and protection processing units. The technology platform is a radio architecture similar to joint tactical radio system/software communications architecture (JTRS/SCA)[2] and eases the scalability of the radio and the portability of software functions across the different members of the family.

Figure 12.1 shows the building block principle of the M3xR family. Based on the common technology platform, individual radios for military airborne applications, tactical radios, and stationary radios evolve. Furthermore, single board radios, e.g. for VDL (VHF digital link) air traffic control applications, are based on the same technology platform. The approach allows for different specific hardware platforms to be used, each optimized to match the specific constraints of the individual application.

12.2.1 General Radio Architecture

The general architecture of the M3xR radio family is shown in Figure 12.2. The operating system and library functions with well-defined application programming interfaces (APIs) isolate the waveforms as applications from the radio platform hardware. Therefore, obeying the restrictions mentioned below, the radio family can be regarded as programmable computers that execute each waveform by their operating system and library functions.

Another well-known view of the SDR concept is shown in Figure 12.3. The software radio architecture is functionally partitioned into different functional modules interconnected by radio control busses (RCBs), which are represented by the vertical arrows. Similar to the ISO/OSI model, we can distinguish between channel processing (including RF filtering, IF filtering, mixing, automatic gain control (AGC)), modulation processing (modulation, demodulation, equalization, digitization, symbol tracking), bitstream processing (e.g. forward error

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[2] See Chapter 2.

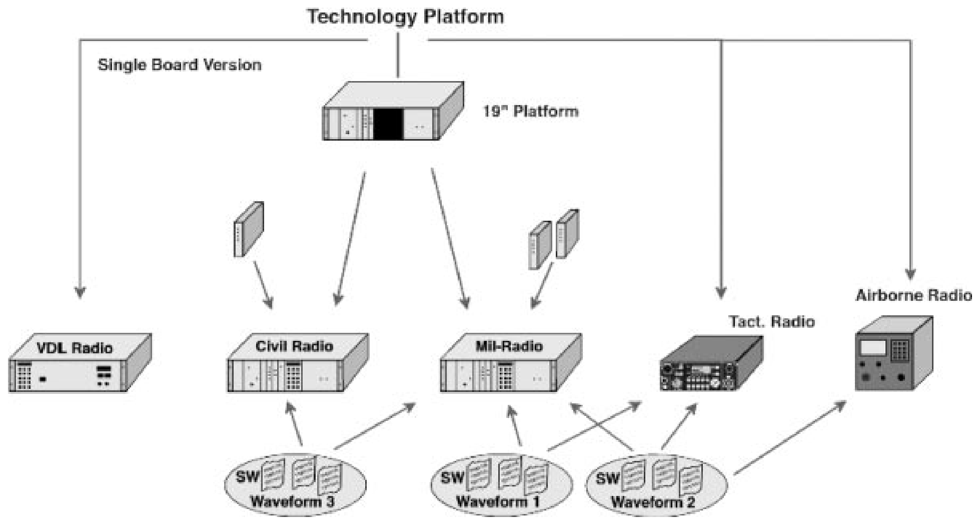

Figure 12.1 The technology platform as a building basis of the three members of the family. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

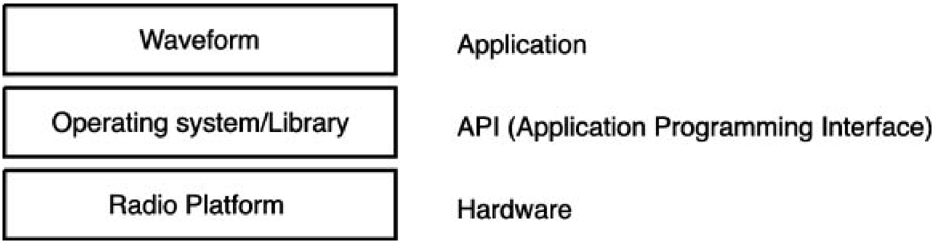

Figure 12.2 Architecture layering separates software applications strictly from the hardware platform. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

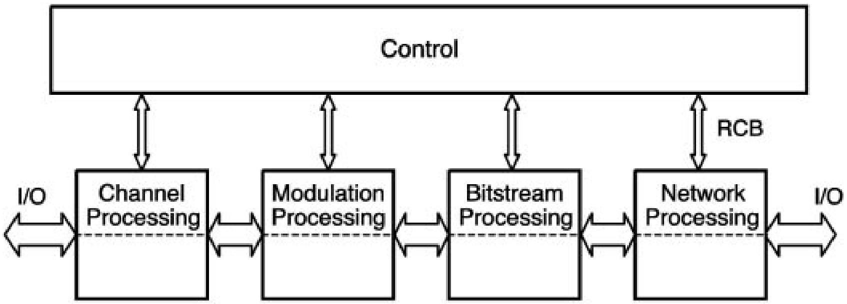

Figure 12.3 Functional partitioning of the software radio architecture. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

control), network processing and protection processing (InfoSec). The protection processing functions (consisting of COMSEC and/or TRANSEC functions), which are inherent in many military waveforms, are normally located within the modulation and bitstream processing units of Figure 12.3.

The modules in Figure 12.3 show the horizontal layering as in Figure 12.2, separating hardware and software parts from each other. The waveform software incarnated by digital signal processors (DSPs) and field programmable gate arrays (FPGAs) holds the control over the main operating parameters and offers an extreme flexibility with benefits for both military/security services and for commercial applications.

Moreover, due to the well-defined and standardized interfaces between the modules, which result in a kind of 'open architecture', modules (both hardware and software) can be readily plugged in or removed. As a result the radio platform is scalable to, e.g. portable or base station applications. As will become clear, this ability to optimize in terms of power consumption, size, and flexibility is of particular importance for the different applications the M3xR family of radios must face.

12.2.2 The Three Ms: Multiband, Multimode, Multirole

The technology-defined platform approach outlined above offers a broad flexibility resulting in the great SDR potential of multiband, multimode, and multirole operation.

12.2.2.1 Multiband

Multiband means that the SDR can operate in a wide frequency range starting from HF (about 1.5 MHz) up to 2 GHz and well above. This multiband feature seems to be commonplace, but nevertheless is essential. As mentioned earlier, the M3xR radios can support both military and commercial waveforms, which normally operate in different frequency bands.

An extremely wideband front end has to show comparable interference and noise performance with existing narrowband radios. Due to co-site operation requirements and potentially hostile interference the military application is more severe [1] compared to commercial applications. As a result, some analog preprocessing is essential and, for trade-off reasons, might be implemented as dual-band front ends (front ends designed for two dedicated frequency ranges). This is especially true for shipborne applications, where many radios are operating simultaneously and where heavy collocation problems occur. For such reasons, the M3SR radio can be equipped with different RF front ends, e.g. one for the VHF/UHF and another for the HF or SHF frequency range.

Due to space, weight, and power consumption limitations, such different front ends cannot be integrated into airborne and tactical radios. Operational performance can be enhanced by software modules, which can correct, to a certain extent, the imperfect behavior of the analog parts, e.g. linearization of the power amplifier by predistortion of the signal. These software modules can be downloaded into the radio if the respective frequency range is required for an application.

Alternatively, due to the modular concept, a certain member of the family may operate in an assigned frequency range with an analog front end optimized to that range.

12.2.2.2 Multimode

Multimode operation requires the SDR to adopt various air interfaces. Besides the military waveforms needed for the (inter)operation of armed forces, it is necessary, e.g. for peacekeeping and humanitarian activities, to adapt to civil standards for global roaming. This applies to both commercial and security communication services. There exists a large number of different standards throughout the whole world, e.g. GSM, TETRA in Europe, IS-95, AMPS, and P25 in the US. Moreover, each standard has special features, with pros and cons depending on the application. One air interface just does not fit all needs.

An ideal software radio should be able to operate on each standard. This is of particular importance, because there is a lack of convergence of wireless standards due to country-specific military and geopolitical reasons. However, the realization of all standards in a single software radio becomes an increasingly complex task, both in terms of required processing speed and power consumption. Fortunately, for most common civil waveforms, commercial chips are available, at least for baseband processing. Due to the modular design of the platforms, the chip sets or modules for these standards may be plugged into the radios with module interfaces adapted to the control structure of the radios, leading in this area to a balanced hardware/software solution to the advantage of the user. If available, chips for military waveforms may be used as well, e.g. InfoSec chips.

12.2.2.3 Multirole

Multirole operation is characterized by using the same radio for several applications, resulting in different demands on the features and interfaces of the radio. Beyond the above-mentioned multiband operation, multirole focuses on different operational scenarios determined by military- and security-service-specific applications. In contrast to commercial cellular networks like universal mobile telecommunications service (UMTS) and GSM, direct mode communication between mobile radios (e.g. tactical radios) is of great importance in military applications – this is a major disparity with commercial applications. Military services require advanced supplementary services, like access priority, dynamic group assignment, late entry, remote disable/enable. Military applications pose a challenge for high level of mobility. Networks are on the move, have to provide redundancy, and show a multi-layered hierarchy. Reliable links within and between arbitrary network configurations have to be established including interfaces to fixed networks such as ISDN/PSTN, local area network (LAN), and wide area network (WAN). Range extension nodes and bridging components between networks are required. The radio architecture must be flexible, to adapt to different roles in those networks. A handheld or tactical radio, for example, does not need the same transmission multirole capability as network nodes, which may serve different standards. As a consequence, the radio architecture should guarantee a flexible and quick radio resource allocation, scaled for various platforms whose radio families are individually optimized in terms of size, weight power, and functionality, depending on whether their platforms are vehicular, ship, or aircraft based.

12.2.3 Protection Processing Units

It is essential for a military SDR to provide TRANSEC/COMSEC functionality, in order to keep the communication private and make it hard to detect and attack. In order to cope with the demands of cryptological techniques, special hardware and software modules have to be provided. Using these modules, red/black (encrypted/plaintext) separation and tamper resistance are accomplished.

All the M3xR radio family uses the same processor module, which is a plug-in for these radios. The software of the waveforms, incorporating electronic protection measures (EPMs) like SECOS, takes into account the red/black separation by distributing the red and black waveform and bitstream processing between different hardware modules.

12.2.4 Radio Control and Human–Machine Interface

Radio control is a typical task of a standard embedded processor system using well-proven software techniques and tools. The statement that the SDR has many elements of a programmable computer is especially true for the radio control processor with its attached remote control and HMIs. The HMI uses APIs for building up the screens. The menu structure can be adapted and parameterized to match the requirements of the different waveforms.

Remote control is based on standard protocols and interfaces. Therefore, commercial off the shelf (COTS) products are widely used to support these interfaces in both lower and higher layers of the protocols.

12.2.5 Preplanned Product Improvement (P3I)

The technology platform systematically follows the preplanned product improvement (P3I) strategy and is designed to cover additional waveforms including applications and frequency ranges, for example:

- national (tactical) waveforms
- additional bands: VLF, SHF
- additional functions: radio terminal, base station, or radio relay
- additional modes: other EPM waveforms in the FH or direct sequence spread spectrum (DSSS) mode, VDL modes 2–4 or LINK 4A/LINK 11

The software-oriented design allows customer-specific requirements to be realized by software downloads without any modifications to the hardware in most cases. Maintenance tools help the customer to initiate a radio upgrade or change of module functionality fast and reliably, optionally by remote control.

The P3I principle essentially contributes towards reducing life cycle costs while keeping the radios at the latest technological level.

12.2.6 Software Download

The principle of the software download is shown in Figure 12.4.

The following items can be downloaded:

- waveform
- library functions
- interface and protocol software

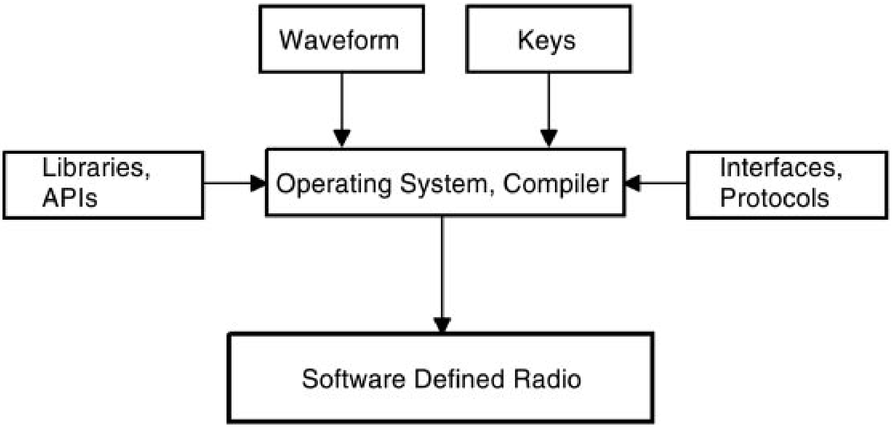

Figure 12.4 Software download principle. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

Furthermore, keys and other operational parameters necessary for the actual role of the radios have to be downloaded as well.

As shown in Figure 12.2, the waveform (the application) is based on the library functions and the operating system. Therefore, if the APIs completely support the waveform, it is sufficient to load the waveform software without downloading new library functions, or to simply parameterize the existing waveform/library functions.

If necessary, new library functions and APIs, which are needed within and are specific for a certain waveform, may be downloaded separately or in combination with the waveform.

In addition to the waveform processing, it might be necessary to adapt the HMI and the remote control interface of the radio in order to allow the operator to activate and to set the parameters of the new waveform. Other necessary adaptations may concern the interfaces and network protocols, e.g. when changing the role of the radio in a multirole environment. When a new interface is plugged in, a download of the interface device driver may need to be performed. Operation-safe maintenance tools are used to support the download. Using preconfigured settings, the operator needs no knowledge about the download process and the distribution of the software on the modules.

The current software download operating principle of the M3xR radios is download using wires or infrared, i.e. preconfiguration in the factory, in a maintenance or operational center, or even in the field. Thus, the person who configures the radio has direct access to it and uses a standard PC with a maintenance tool, which is connected to the radio. For this reason, an easy to operate, but highly sophisticated, password access restriction scheme is used before the download can start. If the radio is remote controlled, this download process is also possible, using the remote control interfaces and network.

Keys and other parameters of EPM schemes have to be downloaded as well. In contrast to the waveform, the keys will be changed regularly, e.g. each day or even for a specific mission. Due to the confidential or secret character of these keys, special care has to be taken. The keys must be stored in the radio in the tamper resistant protection processing module and can never be accessed from outside. For such parameters, download is performed using special key guns.

Furthermore, for the proprietary EPM systems SECOS and SECOM, secure loading is achieved using dedicated encryption schemes via remote control lines and over the air (OTAR, OTAM), using the normal communication links provided. Due to this encryption the keys and other parameters are ‘black’, which means that they can be transmitted even over normal, unsecured lines.

12.2.7 Compatibility with JTRS

The M3xR software radio platform and architecture was designed well before the joint tactical radio system (JTRS)[3] was evolving as a standard for military radios. All relevant aspects from Rohde & Schwarz’ contributions to different programs like Modular Avionics (CNI), FM3TR, and MMITS (SDR) have been considered.

The software design obeys strictly layered design rules, providing the functionality of the different domains as services accessible to the applications. Consequently, the APIs of the domains/software functions can be adapted to CORBA in a straightforward manner, adapting the software structure and therefore allowing the radios to be JTRS compatible.

12.3 Examples of Realized SDRs

The M3xR technology platform provides a sound basis for the three members of the Rohde & Schwarz SDR family, used for various applications and roles by the three armed forces. These various applications demand different optimizations, e.g. wide temperature range, lowest power consumption, or highest flexibility.

12.3.1 Airborne Radio M3AR

The VHF/UHF transceiver M3AR (see Figure 12.5) is designed for aircraft installation (cockpit or electronic bay), enabling secure air-to-air, air-to-ground, and ground-to-air voice and data communication. The M3AR is designed for airborne applications in rotary and fixed wing aircraft, for military air traffic control, and tactical mission control. Military and paramilitary applications require coverage of the UHF frequency range (225–400 MHz). The VHF range, to cover also the civil air traffic control, is included as well. The lower VHF range (30–88 MHz) allows communication with tactical radios.

Airborne radios have stringent requirements in terms of environmental conditions, size, and technical performance. To meet these high demands airborne radios have to be optimized with the technology platform as a basis. The main design goals for the development of the M3AR have therefore been:

- minimum size
- compatible with radios of the type ARC-164 (form, fit, and function)
- housing ARINC 600 as an option
- full performance temperature range −40 to +55°C
- operational performance temperature range −54 to +71°C
- applicability for the worldwide market

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[3] See Chapter 2.

Figure 12.5 The airborne radio M3AR (ARC-164 compatible cockpit version). Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

12.3.1.1 Description

The transceiver is available in different variants. The cockpit transceiver is a stand-alone unit which allows manual control at the control panel. It can be used as a form and fit retrofit for ARC-164 radios and implements superior functionality including frequency hopping techniques for transmission security (TRANSEC) purposes and encryption function for communication security (COMSEC) purposes. Without the control panel the transceiver is suited for being mounted into the aircraft's avionics bay. This unit then is called a remote transceiver. For interfacing the transceiver two interface types are available:

- serial control RS485 or ARINC 629
- Mil-Bus according MIL-STD-1553B avionic bus interface

The transceiver can be controlled from a separate control unit mounted in the cockpit. The control unit implements the same HMI as the cockpit transceiver. Furthermore, the availability of the avionic busses allows integration into a multifunction control and display system.

The VHF/UHF transceiver features a modular design based on the following modules (see also Figure 12.6):

- chassis compatible to ARC-164
- control panel

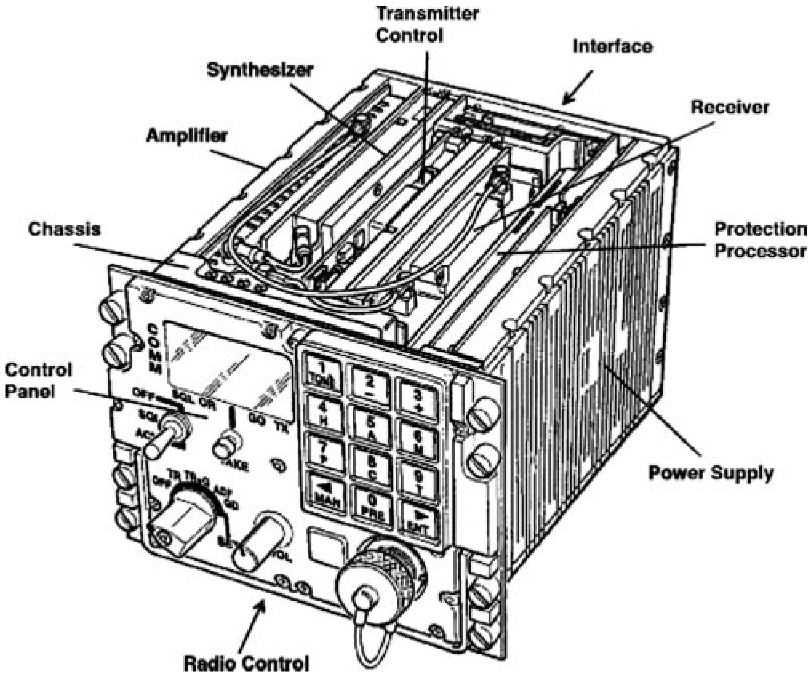

Figure 12.6 Modules of the M3AR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

- protection processor to perform TRANSEC and COMSEC
- synthesizer
- receiver including guard receivers
- transmitter control
- amplifier
- power supply
- interface
- radio control

Figure 12.7 shows the block diagram of the radio outlining the hardware architecture.

The transceiver modules are controlled by the radio control module via the RCB and various serial interfaces. Except for the control panel, all transceiver modules are connected to a flexible wiring harness by means of connectors. The flexible wiring is part of the chassis.

The control panel is the HMI providing switch and keyboard functions for setting of operating mode and parameters. Five light emitting diodes (LEDs) are used to indicate the status of the transceiver. A two-line liquid crystal display shows further information like frequency or mode settings. The control panel is connected directly to the radio control.

The interface module connects all transceiver modules via the RCB with the periphery. Via connectors the required supply voltages are fed and data exchange is effected between the transceiver modules and the external devices. For transceiver operation in receive mode, the RF signal is routed via the amplifier to the Tx/Rx switch and further to the digital receiver

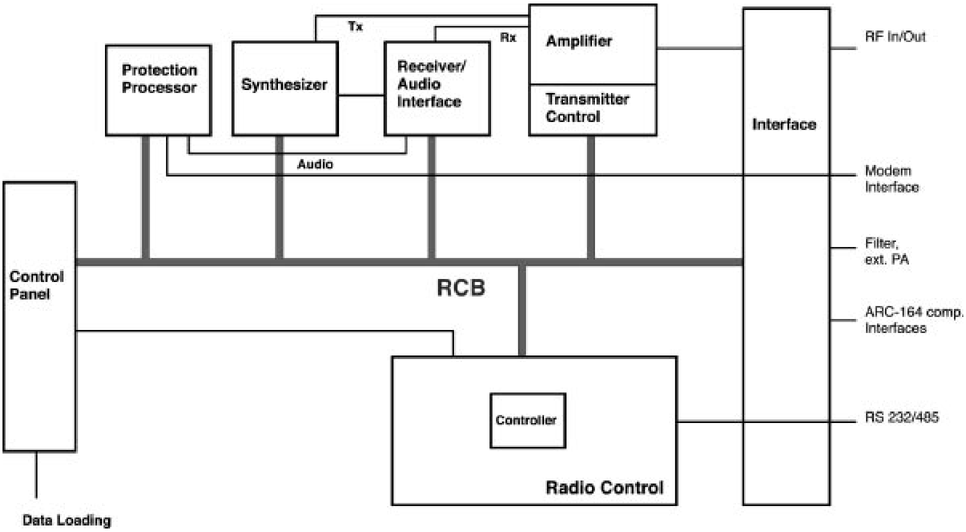

Figure 12.7 Block diagram of the M3AR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

module, which demodulates the RF signal using a software demodulator. The audio signal is routed via the interface module and a connector to the external audio devices. In transmit operation, a modulated carrier signal is taken from the synthesizer to the amplifier. The amplified RF signal is forwarded via the Tx/Rx switch to the antenna output.

The space limitation requires an optimization of the front end, which led to a single module covering all the relevant frequency bands (including the lower VHF range).

A separate guard receiver for the UHF and VHF emergency frequencies of 243 MHz/121.5 MHz can be operated simultaneously with the normal receiver functions, if required. Guard channel operation is not encrypted.

The protection processor carries out all the required EPM functions in both transmit and receive operation of the transceiver. Different EPM modes (NATO, non-NATO) can be activated on this radio. Depending on the combination of these modes this can be done either by simply switching over the transceiver or by software download.

The heart of the radio comprises the radio control and the RCB. The RCB is a digital bus, especially designed to control a digital, programmable radio in an efficient way. All the radio control functions like setting the synthesizer frequency, selecting modem functions, or monitoring the modules are done exclusively by this bus.

The radio control is a processor board containing a general purpose processor. All software is downloaded via serial I/O and programmed into memory.

The software tasks executed on the radio control include among others:

- controlling of all modules inside the transceiver
- providing HMI via the control panel
- interfacing to remote control unit

- getting all control data required for EPM waveforms from the protection processor and distributing them inside the remainder of the transceiver
- starting and controlling of built in test, collecting the results and presenting them on the control panel and remote control

12.3.1.2 Features

Table 12.1 summarizes the key technical features. Since the M3AR is a fully programmable radio the list of mentioned waveforms as well as other features can be extended on request.

Table 12.1 Features of the M3AR airborne software radio

Architecture	Modular design, full programmability
Housing	Compatible to ARC-164; option ARINC 600
Built-in-test	Down to module level
Frequency bands	UHF 225–400 MHz; VHF high 108–174 MHz; VHF low 30–88 MHz
Modulation types	AM, FM, FSK, MSK, PSK (P3I)
Remote control	Serial, parallel ARC-164 compatible, ARINC 629 (P3I), RS485, MIL-BUS acc. to MIL-STD-1553B Control of a radio from more than one remote control unit
EPM (electronic protection measure) modes	SECOS (proprietary frequency hopping mode with high hop rate) Have Quick I/II (standardized frequency hopping mode with slow hop rate) SATURN (standardized frequency hopping mode with very high hop rate) SECOM V (proprietary frequency hopping mode with high hop rate, lower VHF only)
Environmental conditions	Acc. To MIL-HDBK-5400, class 2 modified; full performance −40 to +55°C; operation −54 to +71°C
COMSEC (encryption)	Internal or external, depending on mode selected; embedded NATO COMSEC in ARINC 600 housing

12.3.1.3 Optional Devices

Optional devices are available to complete system and integration needs.

An external high linear power amplifier allows increased output power and hence increased communication range. External fast tuning filters are available as well to improve the collocation performance, which often is a problem in aircraft applications due to the limited decoupling between adjacent antennas.

In order to ease the handling of the radio and to manage the proprietary EPM waveforms, a net management center can be used (see Section 3.4).

12.3.2 Tactical Radio M3TR

The multimode, multirole, multiband tactical radio (M3TR) (Figure 12.8) is the second member of the M3xR product family. M3TR is not restricted to military networks, but by loading the appropriate software can also operate as a terminal in civilian or paramilitary professional mobile radio (PMR, e.g. TETRA) networks. M3TR is a combined tactical radio which is hardware and software configurable for different applications covering the HF, VHF-FM, VHF, and UHF bands in a single mechanical design. It is a multiband, multimode (different high-speed data modes and protocols, different anti-jam modes for HF, VHF-FM, VHF, UHF, e.g. SECOM), and multirole (CNR, PRN, RAP) tactical radio.

Figure 12.8 Tactical radio M3TR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

The radio can be used for different applications as a manpack, in vehicular or in some stationary installations. With its functionality the radio can perform the tasks of the participating units in a mobile subsystem such as:

- combat net radio (CNR)
- packet radio net (PRN)
- repeater (range extension node, REN)
- radio access point (RAP)
- gateway between different nets in different bands

Especially when used as a manpack tactical radio, extremely high demands exist in terms of power consumption and weight. Other design considerations are miniaturization, flexibility, and system capability.

In order to optimize the radio in RF performance the M3TR was designed in two versions. One version covers the HF and the VHF/FM frequency range, the other the VHF and the UHF range. These two versions provide seamless coverage of the transmission range from 1.5 up to 108 MHz, and from 25 up to 512 MHz, respectively. The two versions differ only in the power amplifier and in parts of the radio software. So, with just two versions, the M3TR transceiver covers the whole spectrum from short wave through to the UHF band.

Thanks to optimized protocols and waveforms M3TR attains high data rates for digital voice, real-time video, and visual display data. Beyond line of sight (BLOS), e.g. HF, offers up to 9.6 kbps user rate per 3 kHz channel, while in the line of sight (LOS) case VHF/UHF provides up to 64 kbps per 25 kHz channel. In command systems this ensures, among other things, automated data exchange, for example for online position display and distribution. Preplanned product improvement (P3I) enables to subsequently integrate planned and future methods in the equipment through simple software upgrades.

Different communications standards exist even within NATO and new ones are still being created. Examples are Have Quick I and II, SATURN for UHF, or the ‘HF-House’ (including Automatic Link Establishment, hopping according STANAG 4444) for the short waveband. As a SDR, M3TR can be made compatible with almost all existing EPM radios. It is interoperable with legacy communication systems and supports growth for new requirements.

The use of open system standards, like TCP, Ethernet, and well-defined interfaces within the radio makes M3TR scaleable to match the communication requirements of different users and furthermore extendible to support further growth and changes.

Comprehensive multirole features allow its easy integration into tactical communication networks, e.g. as a functional terminal in a subnet, like CNR (voice and data half-duplex transmission in combat networks) or PRN (multi-hop functionality for packet data transmission, adaptive routing of messages in case of jamming or relocation). M3TR can also act as an interface between the subnets and as a REN for user voice and data services established among radios out of range. Playing the role of a RAP it can establish an interface to fixed networks, e.g. ISDN/PSTN, LAN, WAN, and standardized bus systems, e.g. RS485, and to data interfaces, e.g. RS232, RS422, and MIL-STD-188-114A. It also offers intelligent gateway and relay functions.

12.3.2.1 Description

The architecture determines important features of a SDR such as upgrade capabilities, performance, and versatility of the radio. Power consumption and versatility are among the most important features for a tactical radio product. The architecture of the M3TR was designed to meet this capability and is depicted in Figure 12.9.

The tactical radio M3TR consists of the following modules:

- housing
- radio controller
- power amplifier VHF/UHF or HF/VHF-FM with integrated antenna tuning unit
- RF unit
- front panel
- power supply
- protection processor (optional)

The radio controller, as a central module of the M3TR, controls the entire radio and handles all user voice and data services supported by several interfaces to the radio components. The most important of those interfaces is the RCB, which addresses all the modules inside the

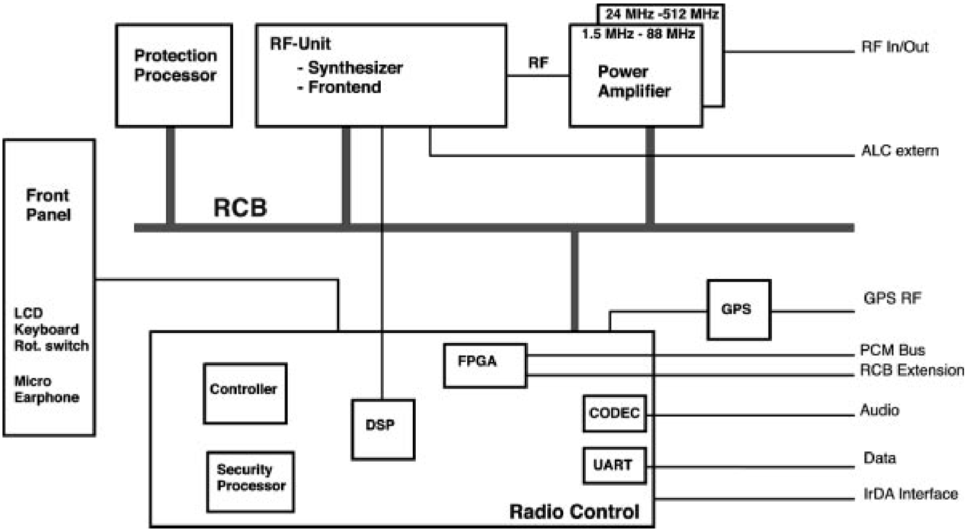

Figure 12.9 Block diagram of the tactical radio M3TR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

radio including an interface for external test control and monitoring at the connectors of the modules. The RCB-Master within the radio controller's FPGA is configured by the central control microprocessor after power-on. The RCB delivers, for example, information and control data like bandwidth and carrier frequency.

The overall signal processing power consists of one central general purpose processor, several DSPs, and security processors, interlinked and initialized by FPGAs. A total storage capacity of 25 Mbytes allows up to 99 default settings (presets), including several EPM methods, to be stored simultaneously. The presets contain all the variable parameters of the selected method, such as hop sets, modulation modes, and addressing.

The optional protection processor allows the use of waveforms with high demands on computing power. When EPMs are employed the protection processor guarantees secure tap-proof links through its use of embedded ciphering procedures and synchronization signaling data. The protection processor allows several waveforms to be loaded simultaneously and any one of them to be selected for operation without the need for download.

A high-speed digital interface provides the connection between the digital IF processing on the radio controller (DSP) and the IF sampling/IQ-modulation, which takes place in the front end of the RF unit. The transmit signal is generated and modulated by digital I/Q-modulation and mixed up in two steps to the requested transmission frequency. Afterwards it is amplified and filtered to attenuate spurious noise.

The power amplifier amplifies the transmit signal and filters out unwanted harmonics. The internal antenna tuning unit as an optional part of the power amplifier is responsible for antenna matching. In receive mode the harmonic filters increase the image rejection and improve the preselection performance. In addition to that, the receiver input protection forms part of the power amplifier unit.

The radio frequency unit (RFU) is divided into three main sections: the front end, the synthesizer, and the RFU controller.

The front end is mainly composed of input image and IF rejection filters, mixers, channel filters, amplifiers, and the AGC. In receive mode the incoming signal is low pass filtered for HF (0–30 MHz) or tuned band pass filtered for VHF/UHF and mixed in three steps down to an IF, where it is sampled and digitized by means of a 16 bit A/D converter. While the estimated received signal strength adjusts the variable gain within the AGC loop, the received data are handed over to the first DSP in the radio controller. In transmit mode a direct digital synthesis chip generates modulated IF signal according to the data from the radio controller. After filtering, amplification, and mixing the final transmit signal is filtered by the tuned HF/VHF/UHF pass bands to reduce spurious emission and noise.

The synthesizer, controlled by means of a reference clock oscillator, supplies all local oscillator and clock signals of the radio, e.g. all mixer frequencies and the bus clock. The synthesizer monitors the PLL and provides test frequencies to be used by built-in-test procedures.

The RFU controller processes the signaling and user data from the radio controller and delivers it to the front end (e.g. for switching, tuning, preselection control, power management, AGC) or synthesizer (e.g. for gain loop control) and vice versa, e.g. signal strength measurement and test report.

The power supply module has to deliver the required voltages with very high efficiency, since this determines significantly the power dissipated in the radio and thus the operational lifetime between battery charges. It consists of low distortion-DC/DC-converters to deliver the supply voltages, the high-side-switch for power-on and filters for the supply voltages. EMC filters are required for all power and control lines to the rear power supply connector. Despite the very high computing power provided by a central processor and several DSPs, the battery supply can sustain operation for up to 57 h. This is achieved by the use of power-saving components and efficient power management.

In the standard manpack application with battery pack, external devices can be connected via the 22 pin data connector and the 10 pin voice connector. The rear connector is used for feeding power and to transfer data to and from the battery pack.

The removable front panel provides the HMI as well as the audio interface; microphone and earpiece are built-in.

If used together with a vehicular mount, additional signals on the rear of the radio are available to allow interoperation with additional power amplifier, automatic tuning unit, switching unit, and other peripherals.

Interfaces on the rear connector are:

- 10/100 Base T
- two PCM- (TDMA-) busses
- serial radio control bus
- RF I/O
- ALC interface
- power supply

12.3.2.2 Features

Table 12.2 summarizes the key technical features of the M3TR tactical radio.

Table 12.2 Features of the M3TR tactical software radio

Architecture	Modular design, full programmability
Dimensions	199 mm × 74 mm × 234 mm
Built-in-test	Down to module level (PBIT, CBIT, IBIT)
Multiband	Tx: 1.5–108 MHz; 25–512 MHz Rx: 1.5–512 MHz
Modulation types	AM, FM, FSK, MSK, PSK, special types can be realized by software download
Remote control	RS232; Ethernet
Modem functionality	Up to 64 kbps for real-time data and video
Network integration	Internet/Intranet access via IP-interface (UDP/TCP)
Radio networking	Packet radio network; TDMA; TCP/IP
EPM (electronic protection measure) modes	SECOS (proprietary frequency hopping mode with high hop rate) Have Quick I/II (standardized frequency hopping mode with slow hop rate) SATURN (standardized frequency hopping mode with very high hop rate) SECOM V (proprietary frequency hopping mode with high hop rate, lower VHF band) SECOM H (proprietary frequency hopping mode with low hop rate, HF only)
Environmental conditions	Full performance −25 to +55°C Operation −40 to +70°C
COMSEC (encryption)	Internal or external, depending on mode selected
OTAM (over the air management)	Wireless rekeying, zeroing, and reprogramming of radios by ciphered transmission and access protection
Multiplexing	Simultaneous voice and data transmission in one channel

12.3.2.3 System Aspects and Optional Devices

The multirole features of a software defined tactical radio are mainly determined by its ease of integration into tactical communication networks. In addition to its use as a tactical terminal in the respective subnet, e.g. CNR or PRN, such a radio can also act as an interface between the individual subnets. M3TR can be used on diverse platforms and features interfaces to LANs and WANs such as Ethernet, ISDN, or ATM, as well as providing intelligent gateway and relay functions, such as autorouting of a selective call for subscribers outside the network. Thus, an optional switching unit provides interfaces for, in principle, all land-based communication networks. Connections to ISDN/PSTN, TCP/IP, UDP as well as to serial and optical interfaces of data terminals are provided.

The interoperation with the switching unit is realized by means of two PCM busses which connect to the M3TR. Audio and FSK signals, interprocessor signaling, and low level signaling signals are transferred between the M3TR and the switching unit.

Further additional external components (e.g. 400 W HF power amplifier, 50 W UHF power amplifier, antenna tuning unit, switching unit (RS232/485, Ethernet, ISDN interfaces), co-site filters for interference-free communication lines) can be connected to the rear of the radio.

An adapted net management center (NMC), similar to that of the M3AR, is also available (see Section 3.4).

12.3.3 Surface Radio M3SR

The M3SR (Figure 12.10) is a modular, multimode, and multi-channel radio, developed for ground-based and vehicle operation. Applicable mobiles are ships, land mobiles, and special aircraft like AWACS. Different variants are available by using a basic radio equipped with different options. Potential military applications include navy, air defense, military air traffic control, and land mobile. It is available today for the frequency range 100–512 MHz. P3I modules will be available to support also the frequency ranges of HF and SHF.

Figure 12.10 Surface radio M3SR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

Air defense typically requires secure, electronically protected communication. Usually these EPMs are frequency hopping methods. There are EPM modes with slow, medium, and fast hop rates, depending on frequency range and standard used.

Naval formations use the UHF range with EPM and link methods like Link 11, Link 4A, Link Y, and Link 22 for ship–ship and ship–shore communication.

Satellite communication in the form of UHF demand assigned multiple access (DAMA) is required by military airplanes, ships, and navy installations on shore. Despite the increasing use of satellite communications HF still is important as an independent backup medium for communication over long distances between ships and between shore and ships.

Civil avionics require the VHF frequency range for air traffic control (ATC) and airline operation service. The modes are amplitude modulation as a legacy mode and in the future VHF digital link (VDL) modes 2, 3, and 4.

During definition and design of the M3SR radio emphasis was set on high modularity, flexibility, extensibility, and performance. These are the prerequisites for real multiband, multimode, and multirole capabilities and can really only be realistically implemented by using a SDR approach.

12.3.3.1 Description

The M3SR has an extremely flexible modular design. It consists of a powerful radio basis (comparable to the motherboard in the PC world) which can accommodate modules of the same or different types. To keep maintenance to a minimum, the individual radio modules are fully independent of each other. If an individual module is replaced, neither hardware adjustment nor an exchange of the radio basis software is required. The radios recognize the installed hardware on booting and perform the correct configuration.

Based on an embedded real-time operating system, the radio basis handles internal communication, interfaces with the outside world, and takes care of audio signal processing as well as device control. Waveform modifications or additional data radio protocols can be implemented by simple software downloads. The user can thus create flexible radio systems from hardware and software building blocks.

The radio basis is identical for all applications. In tune with the philosophy of a universal platform, a variety of software and hardware extensions, called preplanned product improvements (P3I), were conceived for the basic unit. These include extension of the frequency range and also integrated high-data-rate modems.

The radio basis contains one additional slot for a backplane for interface cards. Basic interfaces are also part of the radio basis:

- RS232/RS485 according to EIA RS232/RS485
- narrowband and wideband audio inputs and outputs
- LAN (Ethernet) interface

An oven-controlled reference oscillator (OCXO) for generation of reference clocks for the radio, is also part of the basis.

The basis also includes modules and components, which are relevant for security. A controller module allows protection of equipment serial number and protection against unauthorized software version changes.

Besides the radio basis the M3SR consists of various modules to establish different radio configurations (see Figure 12.11):

- Receiver modules: There are dedicated modules for the frequency bands VHF/UHF and HF, SHF (P3I).
- Synthesizer modules: The synthesizer module generates local frequencies for the receiver and transmitter. If required (e.g. for duplex operation) more than one synthesizer module can be inserted.

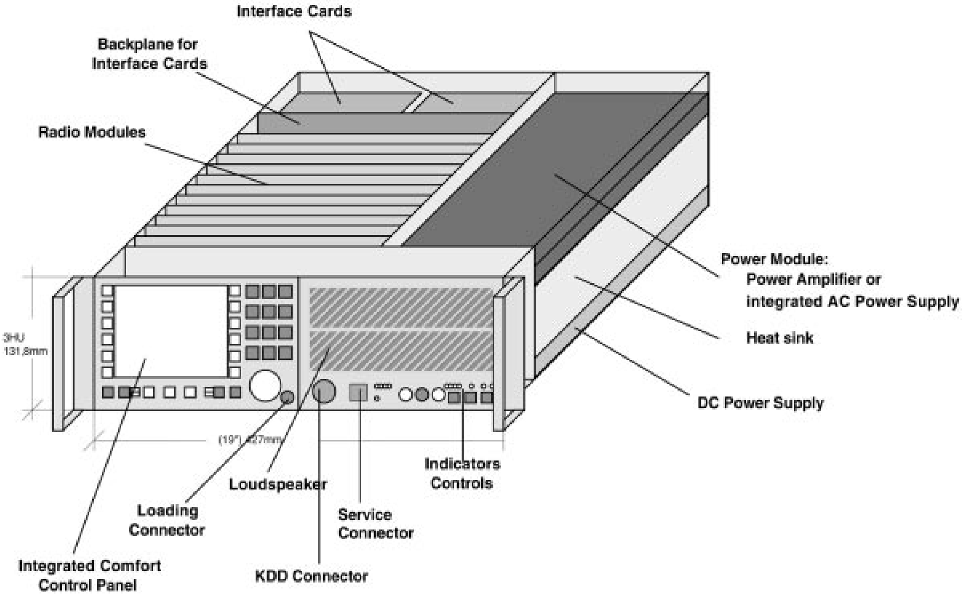

Figure 12.11. Modules of the M3SR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

- Guard receiver module: The guard receiver is able to monitor simultaneously the emergency frequency of the VHF band (121.5 MHz) and the emergency frequency of the UHF band (243 MHz). In case of activity an alarm is given.
- Protection processor module: The protection processor module incorporates powerful signal processing capabilities to perform the data processing for special waveforms.
- Filter modules: The radio can be equipped with internal filter modules, if demanding co-site situations have to be mastered.

Interface cards: Up to six interface cards are possible to adapt the radio to customer-specific interfaces.

The M3SR radio contains interfaces for analog and digital user data, remote control interfaces, control interfaces for external equipment, and interfaces for software download.

Analog interfaces (600 ohm, narrowband and wideband) are provided for operation with legacy systems which may not interface digital voice data. For digital user data, RS232/422/485 can be used as well as Ethernet LAN (P3I).

Remote control can be provided either by connecting a control panel or by connecting an external controller (may be a PC) via a commercial data network. The standard unit for remote control operation will be the comfort control unit, connected via LAN. Instead of using the LAN as connection it is possible to connect the control units by a serial RS232/RS422 point-to-point connection.

For software download the LAN or the serial interface is used. A special protocol for download has been developed to cope with the critical download issues like error-free code transfer, configuration management, and authorization.

In order to support EPM modes the radio has an interface for key loading from the key distribution device (KDD) (for SECOS) or from the fillgun (for Have Quick and SATURN). It is also possible to connect the KDD and the fillgun to the control panels in order to route the data over the control connection to the radio.

For system control, maintenance, and download purposes it is possible to control and monitor the equipment from central points and/or from any point of the system with a remote control and monitoring system or other project-specific solutions.

The software, like the hardware, is of modular design. It can roughly be divided into:

- Control software: This software mainly runs on the radio basis. Tasks are, e.g. to command the radio modules and external auxiliary equipment (filters, power amplifiers) or to perform the built in test.
- Application software: Examples for application software are the different waveform software bundles, e.g. SATURN waveform. This software mainly runs on the radio modules.
- Core software: There are generic core tasks underlying the application software and the control software which often are time critical. Core tasks are, e.g. resource allocation, error handling, or priority handling.
- Library/API: The architecture of the radio (see Figure 12.12) is determined by the need for hardware and software modularity, download capability, and extensibility. To meet these requirements the internal control and communication structure of the radio is key.

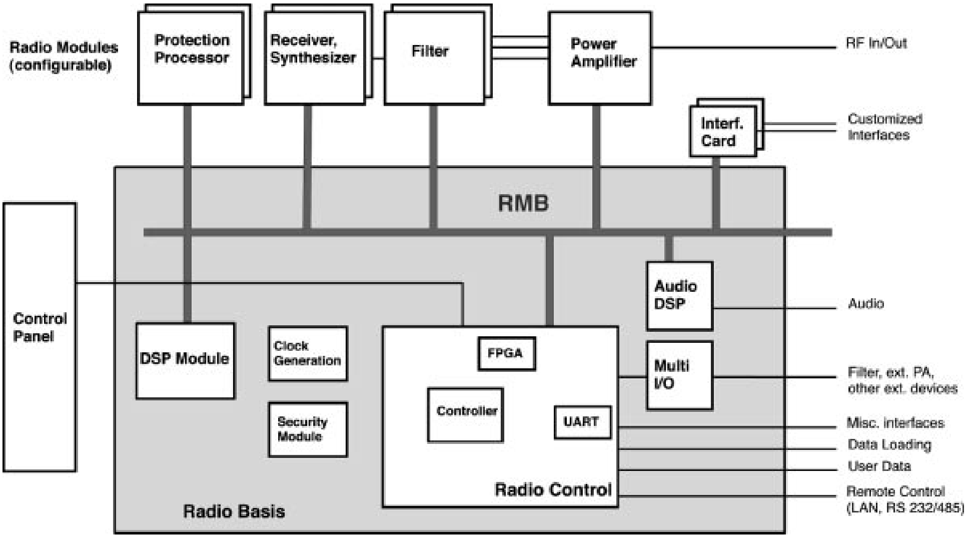

Figure 12.12. Block diagram of the M3SR. Reproduced by permission of Rohde & Schwarz GmbH & Co. KG

Control and communication are performed by the control processor, which is located on the radio basis, and radio module bus (RMB), which interconnects the radio basis and the radio modules.

The software in the control processor performs the following tasks:

- control of the user data transfer between the various radio modules
- control and monitoring of the radio modules
- handling the basic interfaces for remote control, user data, and data loading
- performance of the maintenance functions

The control processor is a powerful general purpose processor with the possibility for performance extension for future additional capabilities as a matter of P3I.

Though the standard interfaces all are located on the radio basis, uncommon or user specific interfaces can be realized with up to six interface cards.

The modular architecture allows the radio to be configured as receiver, multireceiver, transmitter, transceiver, or multiexciter (P3I). These configurations are created solely by means of module combination, together with the loading of appropriate software modules. The radio basis hardware is unaffected by these configuration options.

12.3.3.2 Features

Like the other members of the family, the M3SR is based on a highly modular radio concept with many basic components and optional extension components. The resulting wide variety of radio configurations yields custom-tailored radio systems for use in navy and maritime communication, military ATC, air defense, wireless network systems, mobile stations, special aircraft (like AWACS). Easy-to-handle plug-in-cards allow for virtually unlimited combinations of features, for example:

- up to four parallel communication lines (P3I)
- split-site operation even with proprietary EPMs: transmitter and receiver pairs may be organized as one logical radio
- standard and crossband relay mode, e.g. VHF ↔ UHF
- software-configurable interfaces for extremely easy system integration

The radio is not only capable of different EPM methods like SECOS or Have Quick II, the operator can switch between these prestored EPM methods online.

The main technical features are summarized in Table 12.3.

12.3.3.3 System Aspects and Optional Devices

Normally a stationary radio is installed as part of a complete system and not as stand-alone equipment. To provide applicability in a wide range of different systems, various interface types including different protocols plus optional devices are required. Some options like external filters or power amplifiers require appropriate control interfaces. The M3SR is already equipped with control interfaces compatible with standard Rohde & Schwarz equipment. However, the programmability of the interface cards means that adaptation to almost any equipment is feasible. Systems for air defense or ATC applications, for example, usually are composed of different receiving and transmission sites and may have more than one controller site; often there is the requirement that during quiet periods the control of the whole system shall be performed from a single controller site.

Cosite filters are available in different versions and for different frequency bands. They are

Table 12.3 Features of the M3SR stationary/shipborne software radio

Architecture	Extremely modular design in hardware and software, full programmability of the complete radio
Housing	19”, 3 height units (133 mm)
Built-in-test	Down to module level; all recognized faults can be indicated local or remote; power-up BIT (PBIT), continuous BIT (CBIT), initiated BIT (IBIT)
Failure archive	All detected faults and warnings are stored to be read locally or remotely
Inventory report	All software and hardware configuration parameters are stored to enable complete configuration management of the radio without the need to open the unit
Multiband	VHF/UHF 100–512 MHz without gap HF and SHF can be realized by replacing the RF modules and by loading software accordingly (P3I)
Modulation types	AM, FM, FSK, MSK; special types can be realized by software download
Remote control	RS232, RS422, LAN Integration into data nets by internal LAN hub
EPM (electronic protection measure) modes for NATO	Have Quick I/II (standardized frequency hopping mode with slow hop rate) SATURN (standardized frequency hopping mode with very high hop rate) STANAG 4444 (in case of HF extension) SECOS (proprietary frequency hopping mode with high hop rate)
EPM (electronic protection measure) modes for non-NATO	SECOM H (proprietary frequency hopping mode with low hop rate, in case of HF extension only)
Configurations	Transmitter only, receiver only, transceiver, up to four plain receivers/exciters in one radio (P3I); up to two EPM receivers/exciters in one radio (P3I)
Environmental conditions	Full performance −20 to +55°C
COMSEC (encryption)	Internal or external, depending on mode selected

controlled directly by the radio from a special parallel interface. In case higher RF power is required external transmitter/power amplifiers for all frequency bands can be connected. They receive the baseband signals and control information (e.g. frequency) from the radio and can perform all transmit functions.

The operator requires a control panel and an audio frequency unit for operation.

An external AC power supply establishes the DC voltage, required by the radio for operation. The external power supply is a 19″ unit with a height of 44 mm.

A NMC is available as well to create and handle required data for EPM modes (see Section 3.4).

A remote control and monitoring system is required if the system extends over several sites up to a country-wide dimension.

The media or networks over which the data are transmitted between the equipment are not fixed. They may be chosen/integrated depending upon the particular system requirements or the given infrastructure.

12.3.4 Net Management Center

Modern communication systems need vast amounts of data for mission planning. Therefore, Rohde & Schwarz has developed a NMC to provide for complete turnkey solutions for networks using the R&S proprietary EPM waveforms as well as for normal plain operation. The NMC consists of a key and frequency management center (KFMC), an operation management center (OMC), and fillgun.

The KFMC allows data sets used for the operation of the system to be prepared. These data sets include keys, frequency sets, and operation parameters for the proprietary EPM waveforms. For mission preparation the OMC is used to prepare presets. One preset contains up to 99 preset pages, each of which contains a complete set of preprogrammed operational modes and parameters.

Therefore, the operator of the radio need not care about individual settings of the device, but simply selects a certain preset page, which corresponds to a certain channel or net. All parameters, needed for the operation within the selected net or channel, are then automatically set to the corresponding value.

12.4 Conclusion and Outlook

The SDR approach, requiring a sharp separation between hardware layer and software layer (in the sense of an open system), allows software to be made portable across a range of arbitrary hardware platforms. In turn, these platforms are thus free to be scaled to the differing requirements of manpack, airborne, naval, or stationary deployment, each of which may then be optimized accordingly – e.g. for power consumption, size, or flexibility. The commonality of the software layer guarantees interoperability among these radio families. The software-driven hardware platform also allows an easy implementation of advanced waveforms and functions.

As for a software strategy, the challenge is to create software which is portable to any hardware architecture. First of all, a need for a general programming language describing the radio functionality is apparent [2]. Secondly, in order to achieve full portability, radio APIs are required, which provide the interfaces within the radio to map the waveform description via the operating system or compiler onto any arbitrary architecture. Third, in order to reduce the complexity of the downloading procedure as much as possible, a parametric waveform description should be used, where the parameters determine the main functionalities and make for example the waveform and forward error correction adjustable to quality of service requirements or the varying propagation conditions [3].

The second topic is considered within the software communications architecture (SCA) of the JTRS,[4] which will be a requirement for US radios and may become a de facto standard for military SDRs.

In combination with SCA, research effort has been undertaken to define a general programming language for waveforms. Using such a waveform description language makes it possible to describe a waveform unambiguously in a formal mathematical style. Using standard COTS tools, it will then be possible to generate the software code for the radios. It is likely that new military waveforms will be defined solely using a

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[4] See Chapter 2.

'waveform description language'. One of several possible solutions is described in Ref. [4]. By providing the code based on well-defined APIs, the waveform sponsor can provide hardware independent code, which may be directly used by the operator of the radio for download.

It may be necessary, however, for the radio hardware and API vendor to adapt this code to the actual hardware. The use of the standard APIs of CORBA and standard C++ or Java code puts a heavy additional load on the processors, when compared to optimized code or to waveform-specific ASICs. Therefore, a certain hardware dependent optimization of the code generated by such tools is considered necessary, even if more powerful processors will become available in the future.

The third topic is partly satisfied via the use of APIs. For simple waveforms, it may be sufficient to parameterize existing waveforms to form a new one. However, due to the complexity of modern military waveforms, a complete parameterization of existing waveform code rarely provides a new waveform. Parts of it, e.g. modulators, coders, may simply be parameterized via the API to support the new waveform.

Cosite operation of many radios, e.g. onboard ship, will continue to place heavy demands on the analog processing part. As the technology of analog-to-digital converters and digital-to-analog converters advances, faster devices with higher dynamic ranges will become available [5]. But even with highly linear RF stages, excellent image rejection and dynamic range behavior of the analog radio parts and these converters, the sum load of all signals present in the wide bandwidth military spectrum will surpass the capabilities of these devices/modules today. Therefore, it will still be necessary to use analog RF and IF processing stages, which are designed and optimized for a certain frequency range.

To conclude, a SDR platform offers a broad flexibility and tremendous potential for multiband, multimode, and multirole operation, for defense and other applications. In spite of components, like A/D converters, that still represent a bottleneck in SDR realization, a programmable radio architecture is today not only feasible but, as shown by M3xR, an already achieved solution.

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13

Commercial: Digital Broadcast Receivers and Third-generation Products

David Hislop and Gavin Ferris

RadioScape® Ltd

It is frequently noted in the literature that true software defined radio (SDR) is an ideal; RadioScape has developed techniques, described in this chapter, that have allowed this ideal to be transformed into a commercial reality – already for digital audio broadcasting (DAB) and soon for third-generation (3G) mobile communications. We begin by defining how RadioScape interprets and implements SDR techniques, both during design and at runtime, through a process that facilitates simulation, interpretation, and implementation. Only through such an approach can design engineers manage the challenge of translating today's incredibly complex communications protocols into cost-effective consumer products. The chapter proceeds to describe commercial SDR products for DAB and 3G.

At RadioScape, we believe SDR ought to be represented as: the process of managing complexity whilst maximizing flexibility within the baseband and intermediate frequency (IF) processing of communications stacks by using specific techniques and technologies of non-real-time software engineering in hard real-time domain [1,2]. These techniques include the use of a virtual machine, distributed processing, public interfaces, simulation, and emulation.

The company has actively pioneered SDR techniques in its own products, such as its RST 3000 and RST 5000 receivers for DAB, and in the development of solutions at the heart of third party products, Psion's *WaveFinder®* – a PC-based DAB receiver – and the Texas Instruments® DRE200 and DRE3xy digital radio baseband chips. This SDR focus is also demonstrated in RadioScape's complete portfolio of multiplexing products for digital radio ensembles, now in use by broadcasters around the world. The inherent power and flexibility of the company's SDR approach is further reinforced by the decision to leverage its knowledge in these areas in the development of 3G handsets and base stations (Figure 13.1).

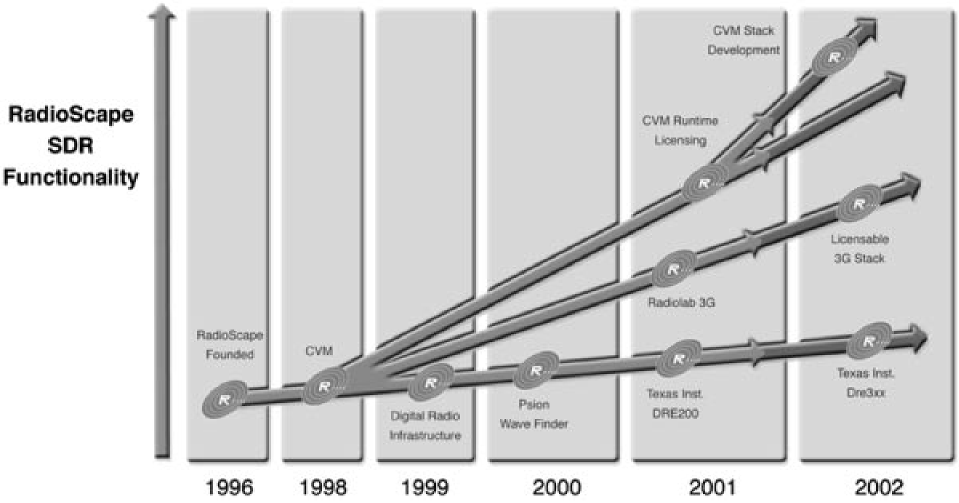

Figure 13.1 Adoption by Psion and TI was the proof-point for RadioScape's approach to software digital radio; RadioLab 3G was the second stage, leading to licensable code for 3G base stations and handset SoC, followed by a licensable CVM for future SoC development

13.1 SDR: Requirements and Implementation

Modern digital broadcast and communication systems require the production of highly integrated, typically system-on-a-chip (SoC), solutions. However, traditional design flows are insufficiently flexible to support the complexity demanded of these designs, particularly next-generation wireless systems. The global development of 3G infrastructure and, in particular, handsets, is proving to be a watershed as many vendors struggle to bring product to market.

Exploring the root causes of this growth in complexity and their relationship to SDR highlights a gap an order of magnitude more severe than the conventional 'design gap', familiar to observers of the silicon intellectual property (SIP) industry.

RadioScape was founded on the assumption that such a gap would, of necessity, emerge as a result of the drive towards evermore integrated, high-bandwidth packet-based systems. It has developed a unique architecture – using SDR technology – to accelerate the development of flexible wireless infrastructure and terminals, and to provide a firm foundation for the company's digital broadcast and communications standards-based products.

At the core of this development is the *Communication Virtual Machine™* (CVM) – a highly flexible development process that combines both design flow and runtime environments. The CVM has been proven successful in the internal development of the TI DRE200 digital radio chip and Psion's WaveFinder radio; it is also providing the foundation of RadioScape's 3G wideband code-division multiple access (W-CDMA) layer 1 development.

13.1.1 The Need for SDR

Demand forecasts for telecommunications traffic created by the Internet alone suggest an increase of between 10- and 25-fold in the next few years [3]. Add to this the irrepressible drive for wireless broadcast and communications protocols to carry this data over ‘the last mile’, and a critical problem immediately becomes apparent: there is only a fixed spectrum capability available. To raise the spectral efficiency (bit/second/hertz) it is thus necessary to use increasingly sophisticated signal processing algorithms. See [4] for a rigorous perspective.

The ubiquitous Moore’s law (also used in [5] and elsewhere) predicts that every 18 months, the number of transistors that may be integrated into a square centimeter of silicon will approximately double. However, if we plot the MIPs requirements of leading edge broadcast and communication standards over time (Figure 13.2), we find that the required MIPs actually exceeds that predicated by this law, making pure software solutions on existing digital signal processors (DSPs) increasingly impracticable. Realistic implementations are having to rely on hardware accelerators operating in conjunction with a programmable DSP core or, more frequently, custom application-specific integrated circuit (ASIC) and SoC-based solutions with inherently high parallelism.

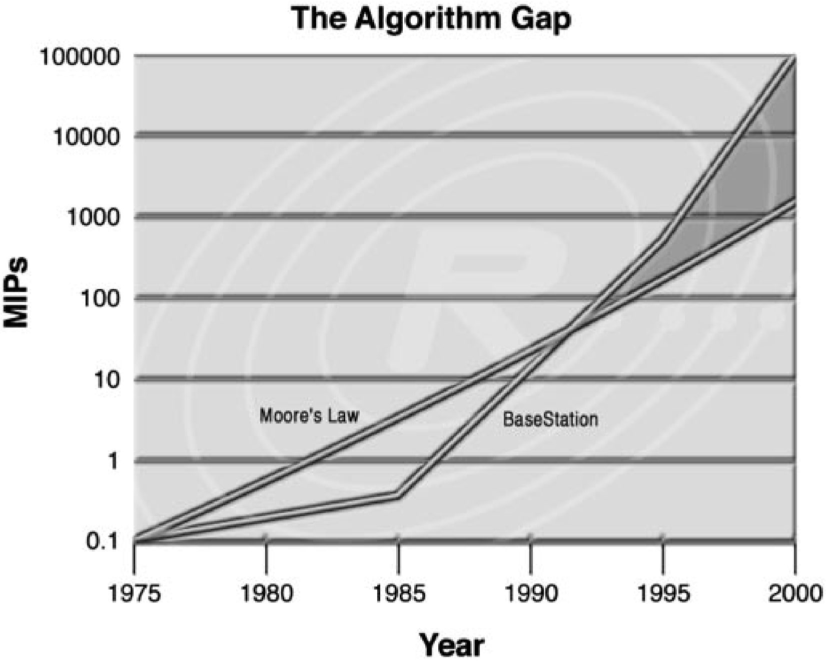

Figure 13.2 As the world goes wireless, spectrum drought requires evermore sophisticated signal processing to increase capacity; the resultant algorithm gap is driving the use of highly parallel architectures

The result is dispersed systems using sophisticated software, communicating via high-performance protocols, which require changes to the functional attributes and physical profile.

13.1.1.1 The Need for Integrated Functionality Created by Multiple DSPs

The advent of powerful chip-based DSPs has enabled engineers to develop a raft of digital solutions to inherently analog problems. Global system for mobile communications (GSM), the world's most widely deployed digital mobile communications system, would not be feasible without high-MIPs DSP components.

GSM is an example of a circuit-switched paradigm and as such the control plane is simple and only requires a small group of relatively simple DSP algorithms in the data path to handle channel encoding/decoding and modulation/demodulation. The switch to a packet-based system entails a multiplexing of logical data paths onto a (generally smaller) number of physical acceleration blocks within the hardware data path, creating significant complexity.

A second problem is convergence of multiple protocols onto a single device, such as GSM and universal mobile telecommunications service (UMTS) in compressed mode.

Further, ever-tightening user equipment space and power consumption budgets mean that the end result has to be integrated onto a single chip. However, due to the complexity and diversity of the standards involved, it is very likely that the solution will comprise several blocks of semiconductor intellectual property (IP) sourced from a variety of vendors. So we can see that the *design gap* identified earlier is rapidly becoming a *design chasm* by the conflicting demands of:

- number, data throughput rate, and complexity of DSP algorithms (vs Moore's law)
- control plane complexity
- multi-protocol (standard) co-location
- increasing power efficiency
- decreasing time to market

Conventional embedded communications product development techniques cannot cope with these conflicts. On the one hand, while digital signal processing code is being subject to new design and implementation techniques as hardware improves, the partitioning for flexibility and reusability is an economic necessity that falls squarely within the remit of SDR.

13.1.2 Project Life Cycle

There are three main methods (design flows) currently in use for digital broadcast and communications baseband development:[1] traditional DSP, real-time software, and full hardware generation. All demonstrate significant shortcomings when exposed to the complexity shifts identified earlier. Understanding when high-MIPs processing is absolutely essential and how high-MIPs and low-MIPs elements interoperate within a typical communication system is the key to the problem.

13.1.2.1 Traditional DSP

Various software modules running on the same DSP can easily intercommunicate; some even provide for simple resource profiling of high-MIPs routines. However, they typically lack

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[1] A detailed review of various aspects of hardware and software aspects of software radio may be found in the companion volume to this one, entitled *Software Radio: Enabling Technologies*, Tuttlebee, W. (Ed.), Wiley, Chichester.

integration with (distributed) real-time software systems, making them less than ideal for managing increasing control plane complexity. Also, their inability to partition between software and (crucially) hardware, and the absence of behavioral simulation tools, seriously limits their usage in designing modern, high-MIPs and high-parallelism products.

13.1.2.2 Higher Layer 'Soft Real-time' Software

Software engineering – for example using specification description language (SDL) and C++ – is good at dealing with the multi-threaded complexity that emerges when building complex real-time systems such as 3G stacks. However, the inability to deal appropriately with either hardware or real-time DSP software has meant that it is normally only used for stack layers 2 and above.

13.1.2.3 Hardware Generation

'ASIC flow' is a common phrase among today's semiconductor engineers and many EDA tool chains provide full hardware generation design flows. While these have no problem generating real-time hardware design partitioning, integration with higher level code components and scheduling is a problem EDA tools are only now beginning to address. It is difficult to model how the limited set of resources generated in hardware will be mapped against the higher number of logical (software) processing flows. Although hardware flows do provide behavioral simulation, getting to a resource-checked partitioned design can be very time-consuming.

Importantly, it can be seen that none of these traditional design flows are capable of providing a truly integrated model of the algorithm partitioning across the various hardware accelerators and the high- and low-level software. As a consequence, manufacturers are finding it increasingly difficult to bring complex designs to market on time, and well nigh impossible to produce designs involving multiple protocol stacks and SIP blocks sourced from different vendors.

13.1.3 Solving the Problem

These problems are ultimately about managing points of articulation. Complexity is handled by breaking the underlying problem down at its logical points of articulation. Done correctly, such a breakdown enables multiple vendors to offer reusable, modular solutions that are themselves of a manageable level of complexity.

The CVM addresses the SoC development problem at *design flow* and *runtime* phases (Figure 13.3). The CVM brings a new set of design flow elements to the engineer, accelerating the hardware/software partitioning and high-level transform description that must underpin today's SoC design processes. This is coupled with a new runtime (or virtual machine) that provides a neutral architecture for developing high-level code independent of the underlying high-MIPs transforms. This virtual machine offers parallel scheduling across distributed processors – DSP, CPU, or field programmable gate array (FPGA) – and busses. Finally, RadioScape's generic baseband processor (GBP™), provides a hardware manifestation of the CVM runtime, allowing system testing and validation to proceed in parallel with real hardware development, further shortening time to market significantly.

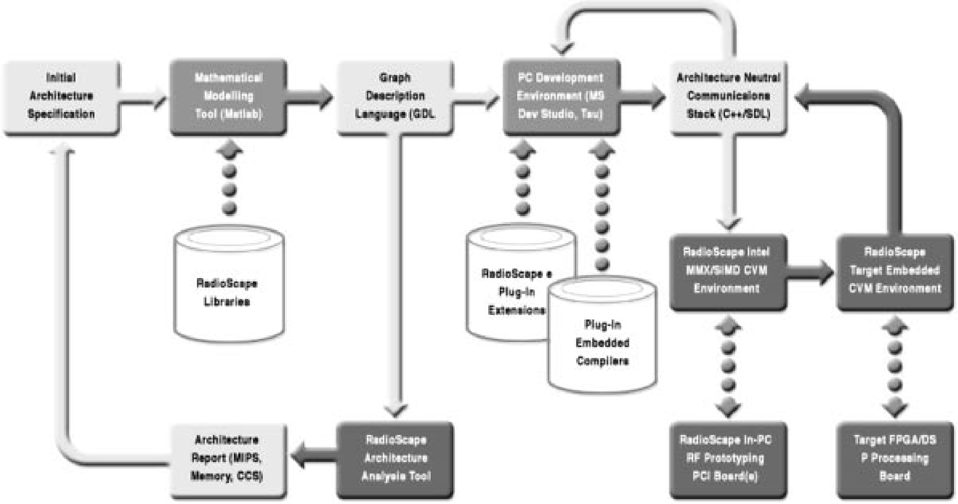


Figure 13.3 The CVM development toolkit creates a completely new design environment for the engineer, accelerating hardware/software partitioning and high-level transform description and underpinning today's SoC design processes

How this approach works is now discussed, followed by how it has successfully accelerated the development of several DAB radio receiver products already on the market.

13.1.4 CVM Design Flow

Chip development conventionally begins with mathematical modeling together with an estimation of the required MIPs and memory for each processing module. Each of the modules making up the decoding stack is then written for the target processor architecture and tested on an architecture-specific simulator. Once the simulation is satisfactory, a prototyping 'rack' can be built with the appropriate hardware processors, memory, programmable logic devices, etc. The basis for ASIC production now exists. See [6,7] for a GSM perspective of design flow.

By clearly identifying three distinct phases, CVM-based design flow provides important additional flexibility to the engineer as a project progresses. The three phases are:

- Pre-partitioning – in which generic transforms (engine types), core processing units and interconnects are sufficiently well defined for behavioral simulation.
- Partitioning – in which high-level stack descriptions are mated to high-MIPs transforms for execution on an underlying substrate, enabling a specific partitioning to be simulated.
- Post-partitioning – in which the above-verified system design is realized by moving it into a conventional tool flow. Two distinct sub-flows open up here: one, executing a behaviorally equivalent version of the full system on the GBP, the other handing the results to design teams for construction in the normal manner.

We examine each of these stages below in a little more detail.

13.1.4.1 Pre-partitioning

The objective of the pre-partitioning phase is to build – from the top, down – a set of descriptions of necessary IP types and instances. Hard real-time transforms are described parametrically, including an interaction semantics model that defines a model's characteristics, such as blocking, threading, etc. By utilizing 'type' descriptions, components are defined in a format that allows subsequent implementation by multiple vendors and – because of the common behavioral model, data types, and so forth – the vendors' offerings will be interchangeable in the design. Importantly, since each implementation must be accompanied by its dynamic resource usage profile, the difference between the components – and hence their key competitive attribute – will be the resources each engine consumes.

It is worth noting that polymorphic data models may be defined from a single engine type in terms of I/O parameters and internal variables. Obviously, the engine type model must cover all of the polymorphs defined.

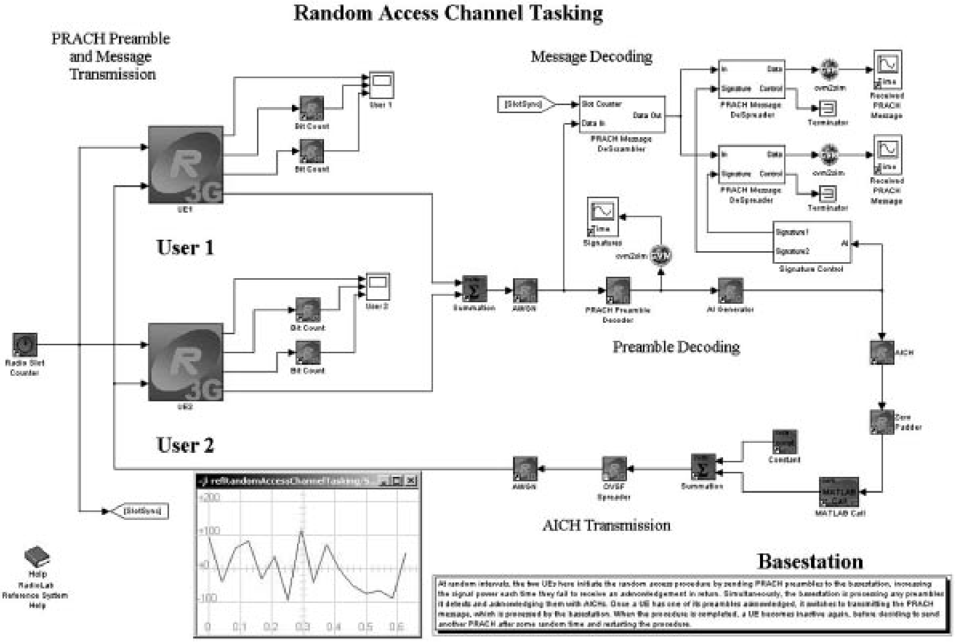
Usage profiles determine the resources an engine consumes when performing its task under specific conditions. Unlike many similar resource profiling tools, the CVM does not require resource models to be static. A resource profile can be expressed as a dynamically executed computation using probability density functions.

The final stage of pre-partitioning is the definition of processing units and interconnects – which must also have their own resource specifications, such as bandwidth for data transfer, bus access latency, etc. Some interconnects will actually be implemented as high-level C++ or SDL code requests on high-MIPs transforms and these can also have resource profiles that stipulate, for example, maximum execution timings.

With each engine modeled at behavioral and resource levels, a complete system design can be rapidly constructed, simulated, and validated without having to invoke the full hardware design flow. At this stage it is possible to generate stimulus files to be used during test. This can be quite straightforward when SDL is used, with TTCN being used to generate stimuli for the higher levels of the stack that will end up as CVM engine requests at the bottom layer of the stack. The SoC developer benefits from this extension of the SDL paradigm – via CVM – into layer 1.

The CVM provides for a set of standard data types, which may be passed between elements, and combined hierarchically to form new elements. Note that the CVM assumes high-MIPs transforms operate on vectors of data and not element-by-element. This approach derives from the fact that modern digital broadcast and communication systems utilize frame- and symbol-based protocols to carry data. It could be argued that, for certain operations – such as a front-end filter that might process an analog-to-digital conversion (ADC) input – sample-based, rather than frame-based, operations would be more natural. However, the vector approach – which also supports optimization for state-space control and pipelining data – has proven entirely acceptable in implementing Eureka-147 digital radio and UMTS products.

For consistency, all models are implemented as CVM transforms which are plugged into MATLAB/Simulink for simulation. A portfolio of standard engine types has been created to date, including a set of simulation elements for W-CDMA FDD (Figure 13.4). Although there is a comprehensive portfolio of engine types, it is entirely possible – and positively encouraged – that even standard specific high-MIPs IP be brought within the CVM. The open architecture of the CVM allows users to define their own data and engine types in addition to providing high-level stacks and engine implementations.



At random intervals, the two UEs here initiate the random access procedure by sending PRACH preambles to the basestation, increasing the signal power each time they fail to receive an acknowledgement in return. Simultaneously, the basestation is processing any preambles it detects and acknowledging them with AICHs. Once a UE has one of its preambles acknowledged, it switches to transmitting the PRACH message, which is processed by the basestation. When the procedure is completed, a UE becomes inactive again, before deciding to send another PRACH after some random time and restarting the procedure.

Figure 13.4 A simple behavioral model of a generate model for a W-CDMA Node-B transceiver, constructed using RadioLab 3G

13.1.4.2 Partitioning

Pre-partitioning is a top-down process that gets the coarse design parameters confirmed quickly and with a high degree of confidence. During the pre-partitioning phase, the components and skeleton high-level code have been established and it is now time to partition the design and stochastically simulate the result to test for design constraint violations. Center stage for this phase is the CVM stochastic scheduler (Figure 13.5).

The key input components have already been derived during the pre-partitioning process:

- algorithm resource maps – the resource usage models of particular implementations of the required engine types;
- the constraint/assertion model is created from the statements inserted into the C++/SDL stack and merged with any other non-inline requirements;
- the stimulus/execution model is provided by the high-level data;
- the interconnect and processor characterizations for a particular target hardware platform may be combined to create an interconnect topology, or may be built from scratch.

The other main input, the partitioning map, is generated using a graphical tool which allows individual engine calls to be mapped to particular engine implementations which themselves are mapped onto specific processing units. To reduce buffering concerns within a multi-threaded DSP environment, or to achieve generalized parallelism within the hardware, multiple copies of an engine can be specified.

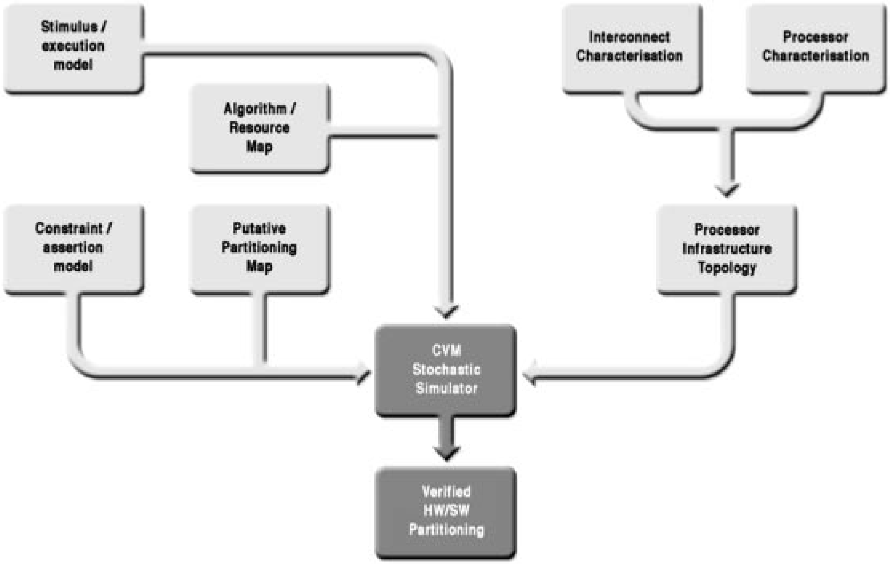


Figure 13.5 By integrating the outputs from pre-partitioning, the CVM stochastic scheduler can create a verified design ready for feeding forward to the hardware design stage

When all the information is available, the CVM's stochastic scheduler executes the model to determine whether any design rules are violated at any point, or if the resource limits of any components – say, the available bandwidth across interconnects – are exceeded. Additional questions of interest are blocking/bus contention and resource violation (memory, thread).

It is now that the new level of flexibility offered to the engineer by the CVM design flow really shows through. Designs can be repartitioned quickly and easily, even when selecting different engine implementations to overcome problems. For example, it may prove necessary to move a Viterbi decoder from a DSP to an on-bus VHDL implementation; provided the behavior of the new accelerator conforms to the same engine type, this process is seamless from the point of view of the high-level stack.

A possible outcome of partitioning is that no suitable engine/resource profile implementation is readily available. One can either redefine the required system performance to avoid the problem, modify the architecture for higher throughput, or simply assume the existence of yet-unwritten IP and define an appropriate resource map for it, leaving it to the hardware stage to satisfy this requirement.

When a successful simulation has been achieved, the partitioning can be taken forward with confidence to begin integration of the real-time IP within a standard design flow.

13.1.4.3 Post-partitioning

In most organizations, the design flow splits once partitioning is complete. The CVM paradigm enables stack/engine interaction – and any further work on the whole system – to be developed prior to having a final hardware substrate, i.e. SoC silicon. Using the GBP, designers can execute behaviorally equivalent implementations of the selected engine types under the control of the high-level code that will run on the final chip. This allows system integration testing and control loop validation to proceed in parallel with hardware production, further shortening time to market.

The parallel path involves the production of the underlying hardware and implementation of any new engines found necessary from the pre-partitioning or partitioning stages. Here, standard toolkits and methodologies are used for hardware development, and standard software development flows for real-time software engine implementations.

One important aspect of the CVM design flow is that it is re-entrant, making it possible to take a working design and simply modify some assumptions to rapidly investigate a new approach. Consider a completed design that uses one vendor's hardware-specific, CVM-compliant high-level code and engines to implement a Eureka-147 digital radio baseband. It is relatively simple to re-engineer the design by merging in say a second vendor's CVM-compliant W-CDMA FDD stack and repartition. Once a new partitioning has been achieved, the stimulus models of both stacks are executed to verify that design constraints have not been violated, before entering the post-partitioning sub-flows in the normal manner.

13.1.5 CVM Runtime

So far we have focused on the design flow paradigm created by the CVM approach. Equally important is the role played by CVM runtime, a virtual machine environment entirely neutral to the final hardware/software topology. CVM runtime provides a hardware abstraction layer, isolating the development code from the underlying hardware and associated real-time operating systems (RTOS) (Figure 13.6).

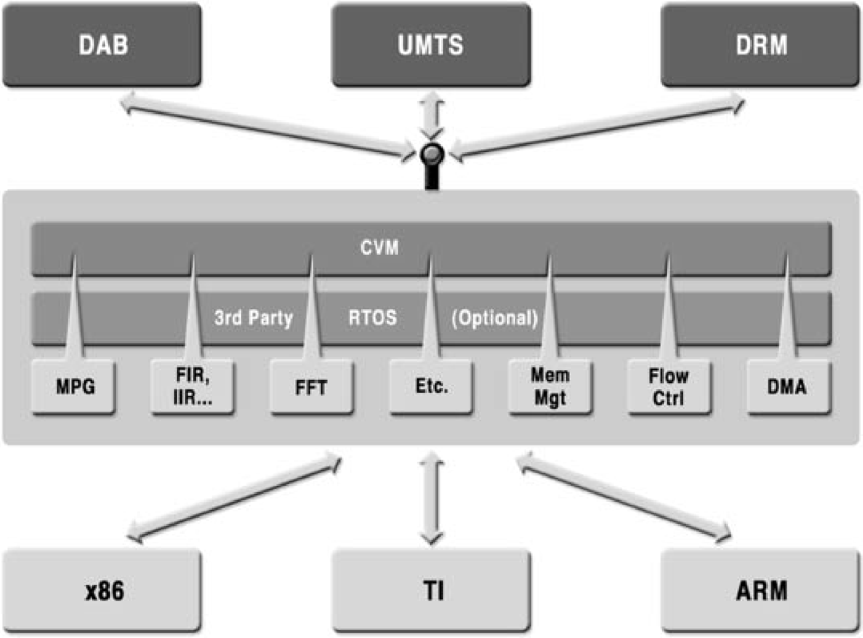


Figure 13.6 CVM runtime isolates the development code from the underlying hardware and associated real-time operating systems, creating an architecturally neutral development environment

For example, if the CVM runtime were to encode assumptions about RTOS calls, say for memory management or multi-threaded code management, it would not be architecturally neutral. Instead, the CVM runtime presents a common threading model, interrupt model, and memory and resource management model to the high-level code, mapping them onto the available primitives of any operating system, such as DSP BIOS, VxWorks, or Win-32/Intel. See [8] for an implementation of a virtual radio.

The CVM runtime resource manager also provides a message-passing endpoint system for inter-engine communication. As noted earlier, the CVM manages data at a vector, not element, level and hence CVM runtime uses smart handles, with data not DMA'd from one processing unit to another unless its contents are specifically accessed. Additionally, CVM runtime's resource management layer manages communication-specific resources, such as uncommitted RAKE fingers that are mapped dynamically onto channels – a feature not commonly provided by a standard RTOS.

13.1.5.1 Parallel Scheduling

As the drive to evermore sophisticated digital processing pushes the cycle requirements of SoCs faster than Moore's law, a natural consequence is to use parallelism through multiple DSP cores, on-chip hardware, or both. However, most RTOS implementations do not support parallel scheduling – and those that do generally take no account of partitioning decisions taken at design time.

In contrast, CVM runtime offers a parallel scheduling system tailored to the design time mappings, requiring only the support of the underlying single-core RTOS and the endpoint communication primitives of the resource management layer in order to operate. This scheduler enables high-level code to request execution of high-MIPs engines on managed data. Further, the CVM runtime goes beyond normal RTOS functionality by enabling different cores to communicate, a key consideration when partitioning execution between say DSP, RISC cores, and custom gate components to interoperate.

In operation, high-level code requests engine execution via the parallel scheduler. The scheduler maps the request onto a particular data path and sends the work unit – normally a package of memory handles – to the appropriate dispatcher endpoint. See [9]. Here, the CVM's engine dispatcher retrieves the request, localizes any memory required and triggers execution; when complete, the dispatcher notifies the control code layer. Effectively, the dispatcher is providing a bridge between the messaging layer and an actual engine implementation, assigning sufficient runtime resources to allow it to allocate memory, raise exceptions, etc.

A seminal feature of the CVM runtime is its maintenance of session state, allowing persistent session data for an engine to be declared for retrieval by subsequent virtual threads. Without this, all data would need to be passed 'in line', a fundamentally difficult feat for components such as time de-interleavers whose behavior intrinsically involves stored memory.

The key goal with the CVM design flow paradigm and associated runtime environment is to make manageable the complexity problem that dominates the design of baseband processing for modern digital communications systems. The CVM not only achieves this but importantly, also de-couples IP production – a major benefit to all parties: producers of 'engine' IP can target specific architectures and still make their technology available to the maximum number of protocol providers; SoC integrators can select high- and low-level IP 'off-the-shelf' for their designs, even bring together multiple protocols on a single device and rapidly determine the design envelope and whether any design constraints of the constituent stacks are violated, before entering into the expense of a full hardware design.

13.1.5.2 Modular and API Based

RadioScape has imposed standards of architecture and modularity more often found in more forgiving environments. Although the use of object-oriented (OO) techniques and the unified modeling language (UML) are not strictly speaking SDR, they are essential to the management of complexity – and result in the presentation of clean interfaces. Accordingly, different tools for different purposes from different vendors can be used to automate testing, for example TTCN/SDL for control, or for integration with other languages or hardware, such as Handel-C for FPGAs.

Software developed using the CVM approach is layered, allowing orthogonal code development. Additionally, common libraries are developed to encourage – and enhance – code re-use. A key advantage that accrues from common libraries – beyond issues such as ease of testing and so on – is that the same code can be used from embedded applications to high-level applications such as modeling and simulation.

13.1.6 Open-IF Interface

Ideally, digital processing should happen as close to the RF stage as possible, where the A/D/A converter and channel isolation filters are of fundamental importance in SDR [10]. Digital downconverters that decimate/interpolate and filter are produced by, for example, Gray Chips® and Harris Semiconductors® [11]. To facilitate the independent development of the RF and analog demodulation of wideband channels, RadioScape has developed an IF interface [12], called Open-IF™ (Figure 13.7). This open digital interface enables user data and control to be sent between the front end and RF utilizing user datagram protocol over IP (UDP/IP). Simple network management protocol (SNMP) is also used for control, managing the RF set-up to facilitate multimode operation, and allowing the definition of a number of application-specific messages to 'tune' the RF.

The CVM does not restrict users to one development language or methodology. It was identified at an early stage that when one considers a FPGA, for example, it would be better to port algorithms to a C-like language, say Handel-C, rather than into VHDL. Handel-C, a product of Celoxica, has extra keywords to persuade compilers to produce VHDL capable of synthesizing a parallel fuse map. It is a well-known rule of thumb that machine-generated VHDL is an order of magnitude slower than its hand coded equivalent. And, although the area of the FPGA mapped by Handel-C is an order of magnitude larger than that of native VHDL – but this is expected to improve with optimizing compilers – the speed degradation is minimal. On a positive note, it takes significantly less time to prototype, debug, and test a Handel-C implementation, as well as maintain or extend the code.

Since it has been said that SDR can only be cost-effective at less than $10 per MIPs, it is perhaps worthwhile exploring the cost implications of this approach. Consider as examples a soft Viterbi decoder and a 3GPP turbo coder interleaver. Our research has shown that it takes around 25% of a 2 million gate FPGA to implement the soft Viterbi decoder and some 10% for the turbo coder interleaver. This means that the FPGA will support four Viterbi implementations each running at about 6–7 Mbit/s – an equivalent of 25 MIPs – or 10 interleavers

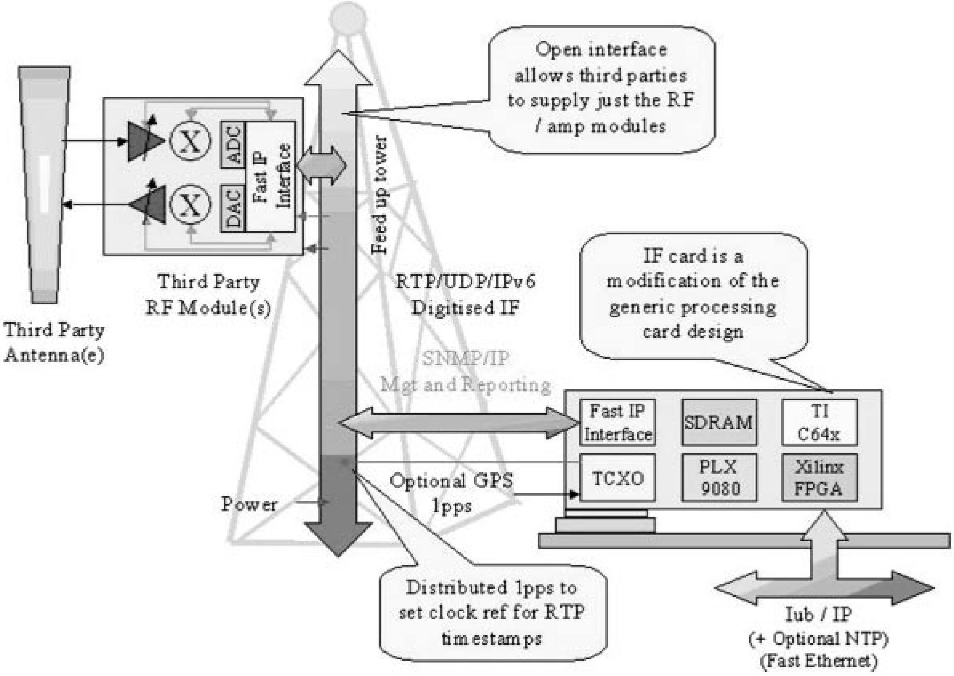


Figure 13.7 Open-IF, an open interface for the communication of IF or I/Q sample data between generic baseband processor cards and third party RF modules, allows engineers to get on with the task of designing without worrying about the tool set

each at 10 Mbit/s, equivalent to 100 MIPs. In mid-2001, the selected FPGA costs $2000, giving $77/MIP for the Viterbi decoder and $20/MIP for the turbo coder interleaver. If one assumes that the cost of a FPGA tracks that of recent DSP chips, which have shown a 20% reduction in cost per MIP in under 12 months, then the above calculations are rapidly approaching the right order of magnitude for economic SDR. See [13] for an informative (but dated) comparison with DSPs as well as [14].

13.2 Market Success: RadioScape's DAB Receiver using SDR

Since 1999, a comprehensive portfolio of products, built round the CVM, has been helping manufacturers, broadcasters, and service providers shorten time-to-market for commercially successful products and services to emerging digital wireless standards (see Figure 13.1 again). Using the CVM, RadioScape has successfully implemented the entire DAB chain on both the transmission side and receiver side, and is active in providing CVM-based solutions for next-generation UMTS/W-CDMA wireless base stations and handsets. The CVM design flow tool chain and runtime environment software may be licensed by companies seeking a fast track solution to next-generation wireless communications, an approach which has resulted in the commercially successful Psion WaveFinder receiver. At the heart of the WaveFinder is a DAB digital baseband chip from Texas Instruments. Texas Instruments is the first vendor to develop a family of commercial chip-based DAB solutions capable of decoding audio and data streams.

Commercial DAB radio receivers are now starting to appear in many forms: car receivers with optional liquid crystal display (LCD) screen or textual display, PC-based receivers which use the computer infrastructure for power, audio output, control, and data display, hi-fi units with LCD screens and textual displays for integration into stereo stacks – and simple portables.

A digital radio receiver has to decode a 2.4 Mbit/s bitstream spread across several hundred or thousand RF carriers, apply error correction, reconstitute the original services that made up the ensemble, and feed the data to a decoder for stereo generation of CD-like audio.

Audio is only one of digital radio's capabilities; the key differentiator from conventional radio is digital radio's ability to carry data services, called datacasting. Non-audio data can be transmitted as program associated data (PAD), or in streamed or packet mode. PAD is embedded in – and hence must be extracted from – the Musicam frames. Packet mode allows several data applications to be statistically multiplexed down a single sub-channel, enabling service providers to make very efficient use of available data capacity.

13.2.1 Professional DAB Products

To prove its SDR approach initially, RadioScape developed its RST 1000, RST 3000, and RST 5000 DAB receivers as personal computer interface (PCI) cards that plug into a PC. These receivers are intended for use by professionals for monitoring DAB transmissions and automating ongoing monitoring and sampling of metrics and transmissions.

The receivers allow users to switch easily between DAB on the band-III (200–300 MHz) and L-band (1.6 GHz) frequencies, with fine tuning available via a VCO. Utilizing a 2 MHz band pass filter, they can scan the two appropriate DAB bands for DAB multiplexes – and dynamically work out the multiplex mode. The environmental management stream is completely defined in software: characterization of the energy distribution in channel and adjacent channels, adaptive nulling of interference, mode recognition, estimating dynamic multipath and coherent combination, ensemble decode equalization and error correction to minimize bit-error rates. This means these receivers can dynamically characterize the transmit channel and transmission scheme and mechanics, probe energy distributions, determine mode, inter-symbol interference, and remove multipaths. Although the RST 1000, RST 3000, and RST 5000 are confined to DAB, its modulation schemes and channel coding, they can easily be extended to IBOC digital AM/FM, and changed to support other coding schemes.

DAB supports a variable data rate and frame-based processing to carry the audio, data, and text-based services that make up the multiplex ensemble. Although the data rates do not vary from frame to frame, multiplex reconfigurations happen dynamically. Users are able to tap into the decode chain and display various measurements, or extract services at will. Importantly, the RST 1000, RST 3000, and RST 5000 all support the VIADAB interface, enabling them to support new data formats underpinning new services by reprogramming the software stacks and DSPs using off-air sources such as a CD or PC.

13.2.2 Psion WaveFinder

Introduced in September 2000, the Psion WaveFinder [15] was the first consumer product to unlock the full power of DAB. Conceived as a digital receiver that connects easily to a PC, WaveFinder allows reception of text, pictures, hyperlinks, and even whole web sites as well as sound, turning the PC into an entertainment appliance that allows users to record MP3 and MP2 files in real time – with no Internet connection required.

WaveFinder is a smart antenna that includes a radio tuner with DSP and which simply plugs into the back of a PC. An on-screen display shows all the stations currently on air; picking a station is easy – just click on a station icon to tune in. If an Internet connection is also available from the PC, listeners can interact with live sites, purchasing the music they are listening to through to related offers for tickets and concerts (Figure 13.8). WaveFinder communicates with the host PC via universal serial bus (USB) using just 30% of that port's 12 MHz bandwidth.

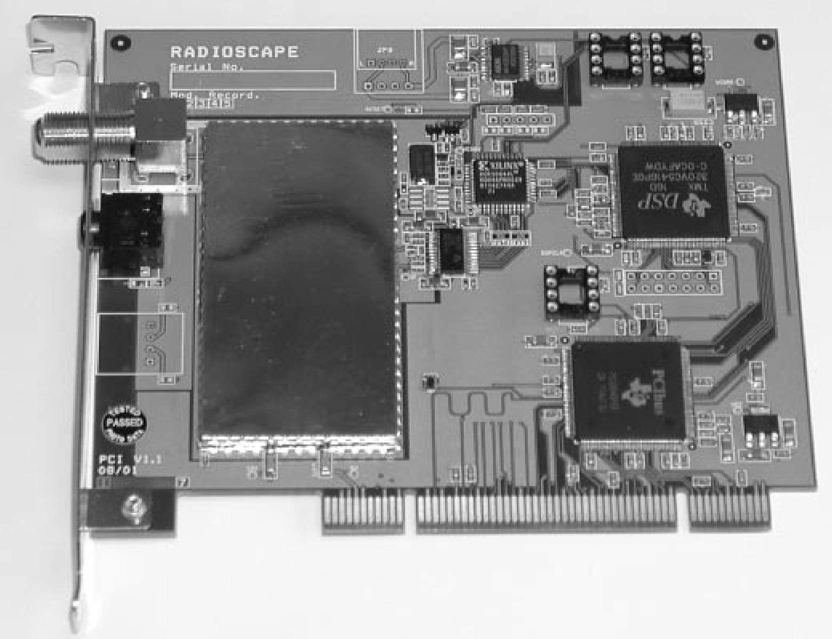


Figure 13.8 RadioScape PCI reference device

As Psion Infomedia, formed to capitalize on the convergence of digital technologies, was exploring the commercial opportunities presented by digital radio, RadioScape was seeking a suitable commercial vehicle for its CVM; WaveFinder is the result. WaveFinder proved to be a landmark in several ways: not only was it the first product to unlock DAB, it was also the first consumer product to prove the power of the CVM paradigm, setting new speed records in porting a solution onto a DSP platform. Within months of its launch, WaveFinder had sold 50,000 units, effectively quintupling the number of DAB receivers in the UK almost instantly.

CVM design flow rapidly provided a technical and economic partitioning of the necessary engines between the PC platform and two TI 5402 DSPs. The TI DSPs, built into WaveFinder's sleek, millennially styled antenna, provide the digital baseband processing, while all memory intensive Eureka-147 functions, such as the Viterbi and MPEG Level 2 decoding, are implemented as software on the PC. The CVM runtime drives the graphical user interface developed by Psion Infomedia, manages the DSP chips as hardware engines, and performs the Viterbi decoding, etc., as software functions, all under the control of the engine dispatcher.

Texas Instruments became interested not only in digital radio technology but also in the record speed with which the CVM design flow achieved partitioning and DSP programming. Working with RadioScape, TI used its TMS320 digital signal processor technology to develop the DRE200, the world's first reprogrammable DSP-based digital baseband receiver solution.

13.2.3 Texas Instruments DRE200/3xy

With on-chip PAD decoding and standard digital-to-analog conversion (DAC) interface compatibility for direct audio output, the ETSI 300–401-compliant DRE200 offers a single chip solution that can decode a single 224 kbit/s DAB audio stream or a 256 kbit/s DAB data stream utilizing less than 75% of the baseband power consumption of its competitors. The design is such that it dramatically shrinks the bill-of-materials normally required for a DAB radio, reducing overall power consumption by 60%, making portable digital radios viable for the first time. In addition, the DRE3xy chip incorporates RadioScape's patented MP3 transcoding – making wireless MP3 a reality for recording and playback – and can also decode all Eureka-147 modes which, when interfaced to an external micro-controller and/or memory, provide a wide range of functions, including multimedia object transmission (MOT) decode and traffic and travel (TPEG) information presentation.

In its basic form, the DRE200 enables low-cost, portable digital radios; the next evolution is expected to herald the introduction of integrated, feature-rich digital radios. Additional capabilities will include parallel decoding of audio and data streams at up to 384 kbit/s, allowing simultaneous multi-channel digital audio/datacasting, and reception of digital AM transmissions as well as FM.

In essence, TI's DRE chips implement a customized version of RadioScape's CVM runtime suitable for supporting the main DAB chip partitions: the primary FFT, demultiplexer and channel decoder, the FIC decoder that drives the synchronization timing, the de-interleaver and Viterbi decoder, the audio (Musicam) decoder and PAD extraction, and the on-chip data decoders.

13.2.4 VIADAB

Whereas audio services in DAB are fully defined by MPEG level 2 specifications, data for datacasting must be coded in such a way that they can be presented to the user on the receiver, requiring data service providers to have an intimate knowledge of the target platform. PC computer platforms are likely to be central to the delivery of DAB data services, and such services will be very important to the success of DAB in an age of competition with other digital broadcast media.

Given the growing number of DAB cards under development for PCs, it is essential that the ability to decode such services is not tied to individual makes of DAB PC card, hampering the realization of data services. Access to services should not be constrained by technology; technologies should compete on price and performance, and services should compete on quality and value. The VIADAB project – versatile information architecture for DAB – has defined an open specification application programming interface (API) for digital radio receivers in a PC environment – essential elements in achieving this aim. Developed jointly by RadioScape and the BBC, with funding from the UK Government's Department of Trade and Industry, the VIADAB specification offers an unprecedented level of flexibility, enabling service providers to write their own data service decoding software. This flexibility has already been taken up in commercial products, not only RadioScape's RST 1000, RST 3000, and RST 5000 professional DAB receivers, but also the Psion WaveFinder supports VIADAB.

The goal of VIADAB is to bridge the 'data gap' by providing a set of middleware definitions and reference implementations. All functionality is provided in the form of 'plug-in' data decoders much the same as today's Internet browser software extends their capabilities. This approach also has the effect of future-proofing VIADAB since out-of-date plug-ins can be quickly and easily replaced with today's new version – automatically, over the air, and with minimal disruption. Although data formats such as MOT are fully supported in VIADAB, offering an easy path to such updates, incompatibilities between platforms – for example between PCs and Apple Macintoshes – push this opportunity well into the future.

For a data service to be successful it must be entertaining or useful, easy to interact with and delivered to the user when they want it and at a reasonable speed. This requires well-designed delivery platforms and software, and that any required user input is simple and intuitive. Given the way the Internet is pervading everyday life, this suggests web technology, HTML pages, and web browsers. Importantly, the 'virtual sockets' layer built into the API allows broadcast web site services to make full use of Java functionality within web browsers, allowing dynamic presentations to be created within an HTML framework.

Potential data services over DAB are limited only by the imagination of broadcasters and service providers. Examples could include: information services in the form of sports results, stocks and shares, weather and traffic updates, commercial services such as advertising – potentially with interactive shopping for CDs, hotel rooms, concert, theatre and travel tickets, and so forth – and entertainment services such as quizzes, etc. Within the VIADAB framework, RadioScape has already developed multimedia object decoders – including a patented MP2 to MP3 transcoder for instant recording of received audio – an http-based web server and streaming IP plug-in.

One example of the need to ensure that the receiver can use the information transmitted is the electronic program guide (EPG), a vital tool for broadcasters and consumers. RadioScape, in conjunction with Unique Interactive, a pioneer of multimedia delivery over digital radio, is developing an end-to-end EPG solution for digital radio: Unique Interactive has developed EPG management software while RadioScape has both the broadcast and receive software; at the receiver end, the VIADAB plug-in software will interpret the EPG data.

13.3 The 3G Challenge

"Since 3G wireless technologies are more difficult to develop and verify than second-generation wireless systems, engineers are faced with finding methods to improve and hasten the design process" [16]. 3G offers a daunting challenge to designers of base stations and subscriber terminals (Figure 13.9). Datacasting is just one of the myriad services expected with the introduction of 3G mobile communications. Many companies are struggling to meet the unprecedented demand for real-time video, digital audio, Internet access, data communication, mobile banking, and so on, targeted for 3G. Terminals must be almost infinitely flexible in design to address such wide-ranging markets.

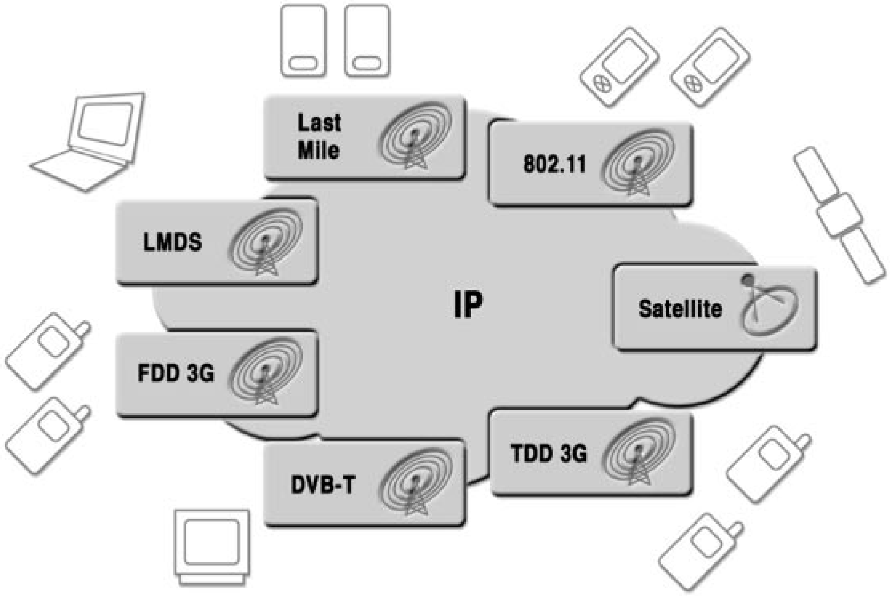


Figure 13.9 Many protocols are involved in connecting terminals to the wired IP cloud, but there is some 80% commonality between the various air interfaces, making flexibility the key to managing emerging communications standards

RadioScape's 3G wireless communications strategy is based upon the premise that SDR is the most viable development technology for network operators wishing to move forward with aggressive 3G infrastructure and user equipment rollout plans without sacrificing future flexibility. At the heart of this strategy is the CVM supported by two major development tools: RadioLab™ 3G and the generic baseband processor (GBP).

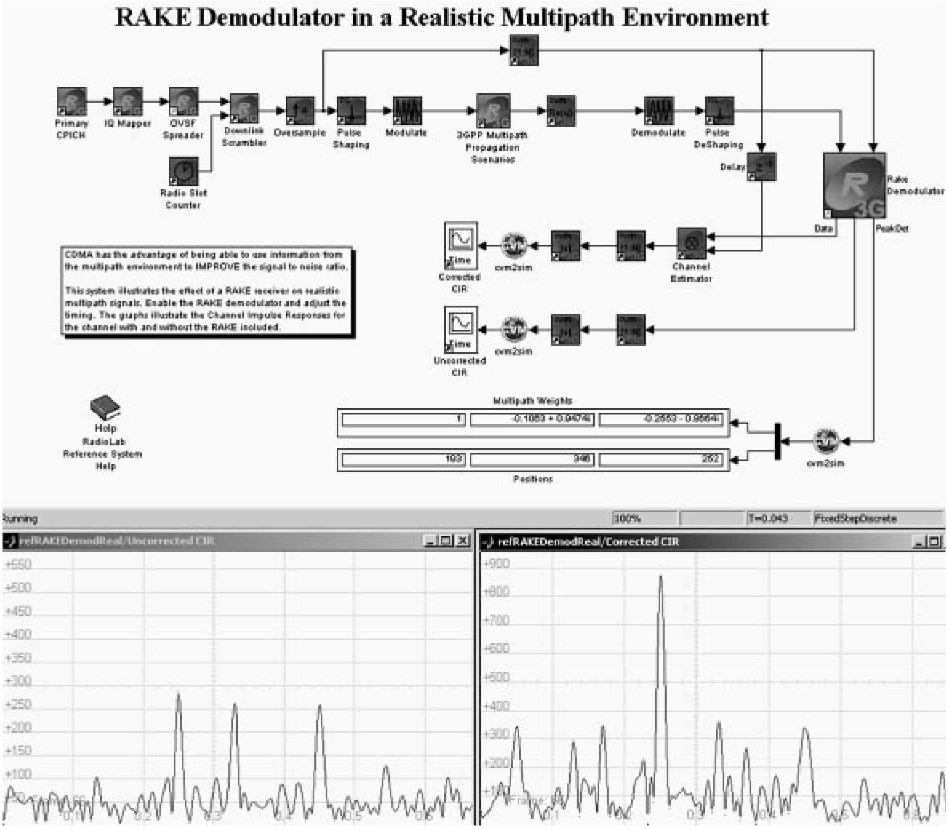
13.3.1 RadioLab 3G

The CVM design flow is the perfect tool for supporting SoC development for next-generation multimode handsets. 3G was conceived to unify existing digital cellular technologies under one umbrella, simplifying global roaming and boosting potential data rates to support mobile Internet access and value added services. However, it is not possible for any one standard to be supplanted by a new standard overnight, raising the requirement for backward compatibility. This objective is further complicated as operators deploy faster packet-based data transmission technologies, such as general packet radio services (GPRS), enhanced data GSM environment (EDGE), and HDR as intermediate (2.5G) stages on the road to full 3G operation.

New standards are generally rolled out gradually, starting in metro areas and building out along major transport arteries as demand grows, and forcing user equipment manufacturers to provide both new and legacy standards within their offerings. Either way, there is the problem of multiple, hard real-time protocols interoperating on a single device. Delivering these leading edge products demands the new, software defined development approach to 3G communications encompassed by RadioLab 3G.

RadioLab enables the linking together of functional blocks to simulate complex models of real-world 3G communications systems. Comprising transport channels, physical channels, modulation and demodulation, channel distortion types and more – as determined by the 3GPP specification – RadioLab facilitates rapid modeling of the significant features in UMTS Layer-1 FDD within Simulink, accelerating handset and Node-B base station development. Additional embedded functionality allows simulations to include bursty traffic, birth/death events, and/or variable-sized data frames, while its interactive capabilities allow engineers to change block properties during a running simulation.

Importantly – prior to committing to silicon in any form – engineers can simulate resource loading under various system partitioning regimes; for example, how many instances of a particular algorithmic engine – say a RAKE receiver element – are required to provide sufficient cover under various statistical loadings? Or, what happens if a data path is implemented in hardware rather than software? Although such decisions are critical, existing toolkits have not addressed them, particularly partitioning decisions with respect to multiple, third party IP blocks. The CVM design flow paradigm – working from the top down –



CDMA has the advantage of being able to use information from the multipath environment to IMPROVE the signal to noise ratio.

This system illustrates the effect of a RAKE receiver on realistic multipath signals. Enable the RAKE demodulator and adjust the timing. The graphs illustrate the Channel Impulse Responses for the channel with and without the RAKE included.

Multipath Weights: 1 | -0.1083 + 0.9474i | -0.2553 - 0.9664i

Positions: 193 | 346 | 262

Figure 13.10 This RAKE processing model for multipath coherent recombining – pre-defined in RadioLab 3G – allows the number of RAKE fingers to be varied and includes a peak search algorithm for determining the strongest multipath signal explicitly enables these sorts of design questions to be answered, and to provide a much more powerful and extensible solution at the same time. RadioLab, with its tools for incremental service development and prototyping, enhances this hierarchical, modular design approach with the capability to estimate processor throughput as well as data rates.

Through the use of custom libraries for MATLAB and Simulink, engineers are able to model in detail – and with bit-exact accuracy – the high-MIPs engine operations. Furthermore, since even the simulation blocks are accessed through the scheduler's indirection interface, it is possible to plug in calls to real hardware implementations, speeding simulation execution.

RadioLab 3G also makes getting started with 3G modem development – and deciphering the 3GPP specifications – much simpler. The inclusion of pre-defined reference models of some of the most interesting and challenging aspects of UMTS subsystems (Figure 13.10) makes the toolkit immediately useful both to experts and those new to W-CDMA development.

When developing a new baseband processing system, it is crucial that the 'rubber hits the road' as soon in the process as possible. It is both highly inefficient and inflexible to wait for a design flow to produce a debugged ASIC – a process largely dictated by the high-MIPs transforms required in modern broadcast and communication systems, and the power and packaging constraints of the final design. Committing to final silicon is a potentially expensive decision and engineers will delay this for as long as possible. Utilizing RadioLab 3G and the CVM enables engineers to simulate in software the target system; however, many will feel insecure with a software-only simulation. The GBP offers the opportunity to delay the decision to go to silicon one more step, further shortening the right first time odds.

13.3.2 Generic Baseband Processor

CVM runtime creates neutral architecture, isolating the development code from the underlying hardware and associated RTOS; the GBP provides an open hardware platform for real-time testing the partitioned design.

Once the post-partitioning phase of the design flow has been entered, the GBP offers a flexible hardware platform on which exact behavioral equivalents of the selected high-MIPs engines can be deployed, accelerating this stage of the development. Assuming the interconnect bandwidths and engine resource profiles on the GBP are at least as good as the final target hardware, then such a system can provide an attractive real-time emulation environment.

The GBP is a modular hardware platform based around a conventional passive PCI backplane, and has a single-board PC for monitoring and boot control. Plug-in PCI cards carry the exact equivalent behavioral engines of the design; each card contains:

- two TI TMS320C6000 series DSPs offering up to 4800 MIPs
- large FPGA offering up to 10 million system gates and up to 12 digital clocks with precision frequency generation to 420 MHz
- at least 32 MB of fast on-board memory
- a PCI bus interface chip supporting I2O message primitives

To exploit this power, the GBP also is equipped with a 1 Gbit/s board-to-board interconnect based upon bus-LVDS technology, including high-speed bus-LVDS I/O to allow either low IF or I/Q data to be passed in digital form to or from an external RF head, and a high-

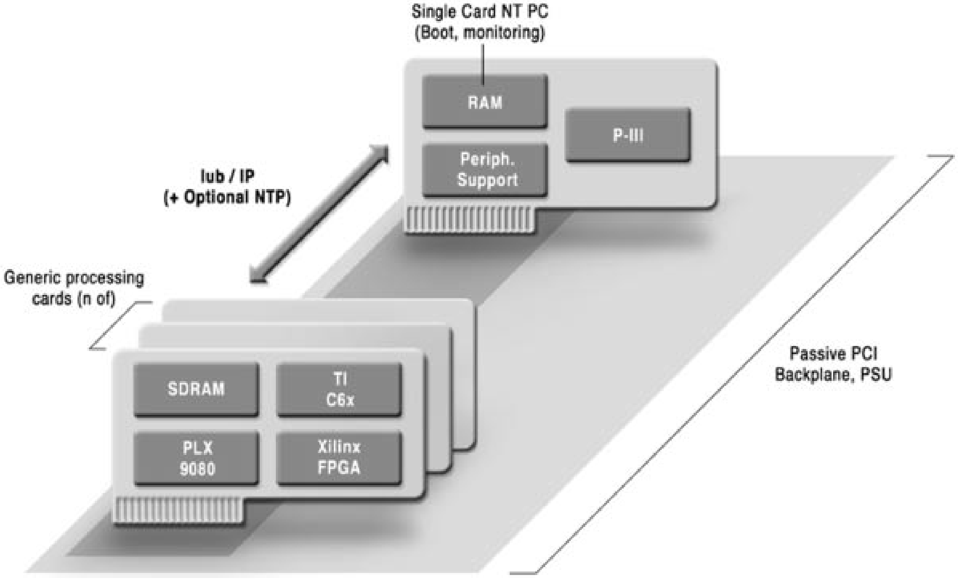


Figure 13.11 The generic baseband processor is a modular hardware platform based around a conventional passive PCI backplane supporting plug-in PCI cards containing 4.8 GIPs DSPs, a 10 mega-gate FPGA with 420 MHz clocks, and at least 32 MB of RAM

speed, external, PMC-standard slot enabling, for example Raceway or Fibre Channel interface cards to be used (Figure 13.11).

An on-board TCXO locks to an external 1 pps/10 MHz supplied by a GPS system, and all sample data are supplied with timing offsets marked relative to that 1 pps directly to the FPGA. RF control commands, such as ‘set center frequency to x MHz at timestamp t’, are multiplexed over the same bearer using SNMP/IP messaging. With Open-IF, appropriate RF front ends for a new standard can be developed rapidly without modifying back-end processing units. Interestingly, as the tractable parallelism of the FPGA and DSPs increase, we believe there will be increasing economic pressure to use the GBP – or an equivalent device – as a real target, particularly for infrastructure development.

It is worth highlighting a hidden benefit of this architecture: because the GBP executes the CVM runtime, a PC with a set of GBP cards installed can act as a high-performance behavioral simulation accelerator for MATLAB/Simulink. Rather than running the local PC version of an engine’s code, the local CVM scheduler can simply redirect the request to an appropriate endpoint on a GBP card containing that equivalent engine.

New 3G wireless Internet devices redefine the mobile concept for consumers, and present enormous commercial opportunities to infrastructure and terminal manufacturers and service providers alike. Moreover, this range of new wireless terminals – personal digital assistants, Internet access devices, and multifunction mobile phones – will require the development of highly complex solutions which combine 2G and 3G communications with digital radio, Bluetooth, or 802.11 functionality.

The CVM, with its key ability to co-schedule parallel communications stacks onto a single chip, institutes a new, software-defined development approach to digital radio capable of supporting the design and deployment of these next-generation solutions. Resource profiling integrated into a top-down design flow, detailed stochastic simulation, and real runtime evaluation tools, ensure that the final design can be quickly and confidently ported to silicon.

13.4 Conclusions

At RadioScape, we believe it is important to distinguish between *runtime* SDR and *design-time* SDR. We define runtime SDR as the use of a generalized hardware substrate which, entirely under software control, performs its specific tasks, but which, because of this software control, has the inherent flexibility to be changed at any moment to exhibit entirely different behavior. There are many advantages to such an approach. However, as the MIPs required for the underlying transforms climb over a period of time faster than Moore's law applications at the cutting edge will be inaccessible to runtime SDR without cost-effective, highly parallel reprogrammable distributed processing devices.

This does not, of course, mean that all applications are affected in this manner; given any fixed MIPs loading for a specified application, general purpose DSPs will eventually catch up. For example, the MIPs loading for Eureka-147 digital audio is sufficiently low that general purpose, 200 MIPs DSPs are able to perform the full demodulation and decoding chain and hence may be executed as a true runtime SDR solution. Indeed, RadioScape's initial product developed with Texas Instruments, the DRE200 digital radio baseband, followed exactly that route. The difficulty lies more with the recent, highly complex standards like 3G which require massive hardware parallelism.

As of Q2 2001, current technology offers cost-effective but MIPs-limited DSPs, and very powerful but cost-limited FPGAs. Consequently, a true runtime SDR platform may be constructed for effective prototyping [17] – as RadioScape has done with its GBP – but such a platform is not yet sufficiently size-, power-, or cost-effective for product deployment. This situation is improving; over the next few years as the demand for spectrum increases more powerful components will be developed.

Conversely, with design-time SDR, progress is not constrained by hardware. At RadioScape, design-time SDR refers to adapting the design complexity management tools and techniques generated by the non-real-time software industry, for use in the hard real-time digital broadcast and communications SoC domain.

We believe that the emergence of 3G will come to be regarded as a point of inflection in this market. Just as those companies that floundered by failing to move from assembly to high-level languages, or, within the non-real-time world, did not adopt procedural, object-oriented and finally component-oriented development, so companies who cling to old design practices will ultimately stumble. Caught between the pincer of the market requiring the increase in size and scope of products and the pincer of a reduction in available time to market new architectures and techniques are required.

Acknowledgements

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software defined radio

Origins, Drivers and International Perspectives

Edited by Walter Tuttlebee
Mobile VCE, UK

Over the past few years software radio has transitioned from an esoteric academic idea to a rapidly commercialising technology that in the coming decade will revolutionise the mobile telecommunications marketplace. Written for industry professionals in engineering and commercial roles, as well as those in academia and research, this book will provide a comprehensive context for all those already active in or entering the field.

Walter Tuttlebee, himself a pioneer of software radio in Europe, has gathered contributions from many of the acknowledged world experts in software radio: leaders operating at the heart of the software radio world today – who share their experience and insight into the background, the present and the future evolution of the technology and the industry. Contributions from North America, Europe and Asia ensure a comprehensive overview of the global SDR scene. The structural approach ensures that the book comprehensively addresses the key issues in the title – the origins of software radio, what has been (and is) driving its commercialisation and what is happening on the international scene.

This book includes:

- a comprehensive review of the origins of software radio in the defence industry
- an insider's view of the origins, evolution, role and activities of the SDR Forum
- a summary of the MIT Sloan study into the drivers of global success in the mobile wireless marketplace
- a review of end user and mobile network operator perspectives of software radio and what the value it can offer
- insiders' summaries of recent SDR research activities in Europe and Japan
- coverage of the regulatory issues associated with SDR and the current approaches being taken in North America and Europe, with contributions from the regulators themselves
- a description of the first steps to SDR standards – the ETSI MExE standard
- descriptions of some of the first commercial software defined radio products, for both defence and commercial applications

Endorsed with a foreword from Joseph Mitola III, 'the father of software radio'

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