COMMUNICATIONS ENGINEERING SERIES

Cognitive Radio Technology

Bruce Fette

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Edited by Bruce A. Fette

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Newnes is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Library of Congress Cataloging-in-Publication Data

Cognitive radio technology / edited by Bruce A. Fette.—1st ed.
p. cm.—(Communications engineering series)
Includes bibliographical references and index
ISBN-13: 978-0-7506-7952-7 (alk. paper)
ISBN-10: 0-7506-7952-2 (alk. paper)
1. Software radio. 2. Artificial intelligence. 3. Wireless communication systems. I. Fette, Bruce A. II. Series.

TK5103.4875.C64 2006
621.384—dc22 2006016824

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN 13: 978-0-7506-7952-7
ISBN 10: 0-7506-7952-2

For information on all Newnes publications visit our Web site at www.books.elsevier.com

06 07 08 09 10 10 9 8 7 6 5 4 3 2 1

Typeset by Charon Tec Ltd, Chennai, India
www.charontec.com
Printed in the United States of America

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List of Contributors

Kenneth Baclawski
Computer and Information Science
Northeastern University
360 Huntington Avenue
Boston, MA, 02115

Charles W. Bostian
Wireless @ Virginia Tech
Bradley Department of Electrical and Computer Engineering
Virginia Tech
Mail Code 0111
Blacksburg, VA, 24060-0111
Email: bostian@vt.edu

David Brady
ECE Dept
Northeastern University
360 Huntington Avenue
Boston MA, 02115
Email: brady@ece.neu.edu

Joseph P. Campbell
Senior MTS
Information Systems Technology Group
MIT Lincoln Laboratory
244 Wood Street, C-290A
Lexington, MA, 02420-9185
Email: j.campbell@ieee.org

William M. Campbell
Information Systems Technology Group
MIT Lincoln Laboratory
244 Wood Street, C-243
Lexington, MA, 02420-9185
Email: wmcampbell@ieee.org

Bruce A. Fette
Chief Scientist
Communication Networks Division
General Dynamics C4 Systems
8220 E Roosevelt
Scottsdale, AZ, 85257
Email: brucefette@yahoo.com

Mieczyslaw M. Kokar
Department of Electrical and Computer Engineering
Northeastern University
360 Huntington Avenue
Boston, MA, 02115
Email: mkokar@ece.neu.edu

Paul Kolodzy
Kolodzy Consulting
P.O. Box 1443
Centerville, VA, 20120
Email: pkolodzy@kolodzy.com

Vincent J. Kovarik Jr.
Harris Corporation
Mail Stop W2-11F
P.O. Box 37
Melbourne FL, 32902-0037
Email: vkovarik@acm.org

Bin Le
Center for Wireless Telecommunications
Wireless @ Virginia Tech
Bradley Department of Electrical and Computer Engineering
Virginia Tech, Mail Code 0111
Blacksburg, VA, 24061-0111
Email: binle@vt.edu

Scott M. Lewandowski
Information Systems Technology Group
MIT Lincoln Laboratory
244 Wood Street, C-256
Lexington, MA, 02420-9185
Email: scl@ll.mit.edu

Preston Marshall
Defense Advanced Research Projects Agency
Email: pmarshall@darpa.mil

Allen B. MacKenzie
Bradley Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University, Mail Code 0111
Blacksburg, VA, 24061-0111
Email: macenab@vt.edu

Joseph Mitola III
Consulting Scientist
Tampa, FL, 33604
Email: jmitola@tampabay.rr.com

James O. Neel
Mobile and Portable Radio Research Group
Wireless @ Virginia Tech
Bradley Department of Electrical and Computer Engineering
Virginia Tech
432 Durham Hall, MS 0350
Blacksburg, VA, 24061
Email: janeel@vt.edu

John Polson
Principal Engineer
Bell Helicopter, Textron Inc.
P.O. Box 482
Fort Worth, TX, 76101
Email: jtpolson@bellhelicopter.textron.com

Jeffrey H. Reed
Mobile and Portable Radio Research Group
Wireless @ Virginia Tech
Bradley Department of Electrical and Computer Engineering
Virginia Tech
432 Durham Hall, MS 350
Blacksburg, VA, 24061
Email: reedjh@vt.edu

Pablo Robert
Mobile and Protable Radio Research Group (MPRG)
Bradley Department of Electrical and Computer Engineering
Virginia Tech
Blacksburg, VA, 24060-0111
Email: probert@vt.edu

Thomas W. Rondeau
Bradley Department of Electrical and Computer Engineering
Virginia Tech
Mail Code 0111
Blacksburg, VA, 24060-0111
Email: trondeau@vt.edu

Jonathan M. Smith
Defense Advanced Research Projects Agency
Email: jmsmith@darpa.mil

Clifford J. Weinstein
Group Leader
Information Systems Technology Group
MIT Lincoln Laboratory
244 Wood Street, C-290A
Lexington, MA, 02420-9185
Email: cjw@ll.mit.edu

Robert J. Wellington
University of Minnesota
9740 Russel Circle S.
Bloomington MN, 55431
Email: rwellington@mn.rr.com

Youping Zhao
Mobile and Portable Radio Research Group
Wireless @ Virginia Tech
432 Durham Hall, MS 350
Blacksburg, VA, 24061
Email:yozhao@vt.edu

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Foreword

This introduction takes a visionary look at ideal cognitive radios (CRs) that integrate advanced software-defined radios (SDR) with CR techniques to arrive at radios that learn to help their user using computer vision, high-performance speech understanding, global positioning system (GPS) navigation, sophisticated adaptive networking, adaptive physical layer radio waveforms, and a wide range of machine learning processes.

CRs Know Radio Like TellMe® Knows 800 Numbers

When you dial 1-800-555-1212, a speech synthesis algorithm says "Toll Free Directory Assistance powered by TellMe® Networks (www.tellme.com, Mountain View, CA, 2005). Please say the name of the listing you want." If you mumble it says, "OK, United Airlines. If that is not what you wanted press 9, otherwise wait while I look up the number." Reportedly, some 99 percent of the time TellMe gets it right, replacing the equivalent of thousands of directory assistance operators of yore. TellMe, a speech-understanding system, achieves a high degree of success by its focus on just one task: finding a toll-free telephone number. Narrow task focus is one key to algorithm successes.

The cognitive radio architecture (CRA) is the building block from which to build cognitive wireless networks (CWNs), the wireless mobile offspring of TellMe. CRs and networks are emerging as practical, real-time, highly focused applications of computational intelligence technology. CRs differ from the more general artificial intelligence (AI) based services like intelligent agents, computer speech, and computer vision in degree of focus. Like TellMe, CRs focus on very narrow tasks. For CRs, the task is to adapt radio-enabled information services to the specific needs of a specific user. TellMe, a network service, requires

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Note: Adapted from J. Mitola III, *Aware, Adaptive and Cognitive Radio: The Engineering Foundations of Radio XML*, Wiley, 2006.

substantial network computing resources to serve thousands of users at once. CWNs, on the other hand, may start with a radio in your purse or on your belt, a cell phone on steroids, focused on the narrow task of creating from the myriad available wireless information networks and resources just what is needed by just one user: you. Each CR fanatically serves the needs and protects the personal information of just one owner via the CRA using its audio and visual sensory perception and automated machine learning (AML).

TellMe is here and now, while CRs are emerging in global wireless research centers and industry forums like the SDR Forum and Wireless World Research Forum (WWRF). This book introduces the technologies to bootstrap CR systems, introducing technical challenges and approaches, emphasizing CR as a technology enabler for rapidly emerging commercial CWN services.

CRs See What You See, Discovering Radio Frequency Uses, Needs, and Preferences

Although the common cell phone may have a camera, it lacks vision algorithms, so it does not know what it is seeing. It can send a video clip, but it has no perception of the visual scene in the clip. If it had vision-processing algorithms, it could perceive and understand the visual scene. It could tell whether it were at home, in the car, at work, shopping, or driving up the driveway on the way home. If vision algorithms show it that you are entering your driveway in your car, a CR could learn to open the garage door for you wirelessly. Thus, you would not need to fish for the garage door opener, yet another wireless gadget. In fact, you do not need a garage door opener anymore, once CRs enter the market. To open the car door, you will not need a key fob either. As you approach your car, your personal CR perceives the common scene and, as trained, synthesizes the fob radio frequency (RF) transmission and opens the car door for you.

CRs do not attempt everything. They learn about your radio use patterns because they know a lot about radio, generic users, and legitimate uses of radio. CRs have the a priori knowledge needed to detect opportunities to assist you with your use of the radio spectrum accurately, delivering that assistance with minimum intrusion.

Products realizing the visual perception of this vignette are demonstrated on laptop computers today. Reinforcement learning (RL) and case-based reasoning (CBR) are mature AML technologies with radio network applications now being demonstrated in academic and industrial research settings as technology pathfinders for CR[1] and CWN.[2] Two or three Moore's law cycles or 3 to 5 years from now, these vision and learning algorithms will fit in your cell phone. In the interim, CWNs will begin to offer such services, presenting consumers with new tradeoffs between privacy and ultra-personalized convenience.

CRs Hear What You Hear, Augmenting Your Personal Skills

The cell phone on your waist is deaf. Although your cell phone has a microphone, it lacks embedded speech-understanding technology, so it does not perceive what it hears. It can let you talk to your daughter, but it has no perception of your daughter, nor of the content of your conversation. If it had speech-understanding technology, it could perceive your speech dialog. It could detect that you and your daughter are talking about common subjects like homework or your favorite song. With CR, speech algorithms would detect your daughter saying that your favorite song is now playing on WDUV. As an SDR, not just a cell phone, your CR then could tune to FM 105.5 so that you can hear "The Rose."

With your CR, you no longer need a transistor radio. Your CR eliminates from your pocket, purse or backpack yet another RF gadget. In fact, you may not need iPOD®, Game Boy® and similar products as high-end CRs enter the market (or iPODs or Game Boys with CR may become the single pocket pal instead: you never know how market demand will shape products toward the "killer app," do you?). Your CR could learn your radio listening and information use patterns, accessing songs, downloading games, snipping broadcast news, sports, and stock quotes as you like as the CR re-programs its internal SDR to better serve your needs and preferences. Combining vision and speech perception, as you approach your car your CR perceives this common scene and, as you had the morning before, tunes your car radio to WTOP for your favorite "Traffic and weather together on the eights."

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[1] Mitola's reference for CR pathfinders.

[2] *Semantic Web*: Researchers formulate CRs as sufficiently speech-capable to answer questions about <Self/> and the <Self/> use of <Radio/> in support of its <Owner/>. When an ordinary concept like "owner" has been translated into a comprehensive ontological structure of Computational primitives, for example, via Semantic Web technology, the concept becomes a computational primitive for autonomous reasoning and information exchange. Radio XML, an emerging CR derivative of the eXtensible Markup Language, XML, offers to standardize such radio-scene perception primitives. They are highlighted in this brief treatment by <Angle-brackets/>. All CR have a <Self/>, a <Name/>, and an <Owner/>. The <Self/> has capabilities like <GSM/> and <SDR/>, a self-referential computing architecture, which is guaranteed to crash unless its computing ability is limited to real-time response tasks; this is appropriate for CR but may be too limiting for general-purpose computing.

For AML, CRs need to save speech, RF, and visual cues, all of which may be recalled by the user, expanding the user's ability to remember details of conversations and snapshots of scenes, augmenting the skills of the <owner/>.[3] Because of the brittleness of speech and vision technologies, CRs try to "remember everything" like a continuously running camcorder. Since CRs detect content, such as speakers' names, and keywords like "radio" and "song," they can retrieve some content asked for by the user, expanding the user's memory in a sense. CRs thus could enhance the personal skills of their users, such as memory for detail.

CRs Learn to Differentiate Speakers to Reduce Confusion

To further limit combinatorial explosion in speech, CR may form speaker models, statistical summaries of the speech patterns of speakers, particularly of the <Owner/>. Speaker modeling is particularly reliable when the <Owner/> uses the CR as a cell phone to place a phone call. Contemporary speaker recognition algorithms differentiate male from female speakers with high accuracy. With a few different speakers to be recognized (i.e., fewer than 10 in a family) and with reliable side information like the speaker's telephone number, today's state-of-the-art algorithms recognize individual speakers with better than 95 percent accuracy.

Over time, each CR learns the speech patterns of its <Owner/> in order to learn from the <Owner/> and not be confused by other speakers. CR thus leverages experience incrementally to achieve increasingly sophisticated dialog. Today, a 3 GHz laptop supports this level of speech understanding and dialog synthesis in real time, making it likely to be available in a cell phone in 3 to 5 years.

The CR must both know a lot about radio and learn a lot about you, the <Owner/>, recording and analyzing personal information and thus placing a premium on trustworthy privacy technologies. Increased autonomous customization of wireless service include secondary use of broadcast spectrum. Therefore, the CRA incorporates speech recognition to enable learning without requiring overwhelming amounts of training, allowing it to become sufficiently helpful without being a nuisance.

More Flexible Secondary Use of Radio Spectrum

In 2004, the US Federal Communications Commission (FCC) issued a Report and Order that radio spectrum allocated to TV, but unused in a particular broadcast

[3] Ibid.

market, such as a rural area, could be used by CR as secondary users under Part 15 rules for low-power devices—for example, to create ad hoc networks. SDR Forum member companies have demonstrated CR products with these elementary spectrum perception and use capabilities. Wireless products—both military and commercial—are realizing that the FCC vignettes already exist.

Complete visual and speech perception capabilities are not many years distant. Productization is underway. Thus, many chapters of Bruce's outstanding book emphasize CR spectrum agility, suggesting pathways toward enhanced perception technologies, with new long-term growth paths for the wireless industry. This book's contributors hope that it will help you understand and create new opportunities for CR technologies.

Dr. Joseph Mitola III
Tampa, Florida

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CHAPTER 1

History and Background of Cognitive Radio Technology

Bruce A. Fette
Communications Networks Division
General Dynamics C4 Systems
Scottsdale, AZ, USA

1.1 The Vision of Cognitive Radio

Just imagine if your cellular telephone, personal digital assistant (PDA), laptop, automobile, and TV were as smart as "Radar" O'Reilly from the popular TV series M*A*S*H.[1] They would know your daily routine as well as you do. They would have things ready for you as soon as you ask, almost in anticipation of your need. They would help you find people, things, and opportunities; translate languages; and complete tasks on time. Similarly, if a radio were smart, it could learn services available in locally accessible wireless computer networks, and could interact with those networks in their preferred protocols, so you would have no confusion in finding the right wireless network for a video download or a printout. Additionally, it could use the frequencies and choose waveforms that minimize and avoid interference with existing radio communication systems. It might be like having a friend in everything that's important to your daily life, or like you were a movie director with hundreds of specialists running around to help you with each task, or like you were an executive with hundred assistants to find documents, summarize them into reports, and then synopsize the reports into an integrated picture. A cognitive radio is the convergence of the many pagers, PDAs, cell phones, and many other

[1] "Radar" O'Reilly is a character in the popular TV series M*A*S*H, which ran from 1972 to 1983. He always knew what the colonel needed before the colonel knew he needed it.

single-purpose gadgets we use today. They will come together over the next decade to surprise us with services previously available to only a small select group of people, all made easier by wireless connectivity and the Internet.

1.2 History and Background Leading to Cognitive Radio

The sophistication possible in a software-defined radio (SDR) has now reached the level where each radio can conceivably perform beneficial tasks that help the user, help the network, and help minimize spectral congestion. Radios are already demonstrating one or more of these capabilities in limited ways. A simple example is the adaptive digital European cordless telephone (DECT) wireless phone, which finds and uses a frequency within its allowed plan with the least noise and interference on that channel and time slot. Of these capabilities, conservation of spectrum is already a national priority in international regulatory planning. This book leads the reader through the technologies and regulatory considerations to support three major applications that raise an SDR's capabilities and make it a cognitive radio:

1. Spectrum management and optimizations.
2. Interface with a wide variety of networks and optimization of network resources.
3. Interface with a human and providing electromagnetic resources to aid the human in his or her activities.

Many technologies have come together to result in the spectrum efficiency and cognitive radio technologies that are described in this book. This chapter gives the reader the background context of the remaining chapters of this book. These technologies represent a wide swath of contributions upon which cognitive technologies may be considered as an application on top of a basic SDR platform.

To truly recognize how many technologies have come together to drive cognitive radio techniques, we begin with a few of the major contributions that have led up to today's cognitive radio developments. The development of digital signal processing (DSP) techniques arose due to the efforts of such leaders as Alan Oppenheim [1], Lawrence Rabiner [2, 3], Ronald Schaefer [3], Ben Gold, Thomas Parks [4], James McClellen [4], James Flanagan [5], fred harris [6], and James Kaiser. These pioneers[2] recognized the potential for digital filtering and DSP, and prepared the seminal textbooks, innovative papers, and breakthrough signal

[2] This list of contributors is only a partial representative listing of the pioneers with whom the author is personally familiar, and not an exhaustive one.

processing techniques to teach an entire industry how to convert analog signal processes to digital processes. They guided the industry in implementing new processes that were entirely impractical in analog signal processing.

Somewhat independently, Cleve Moler, Jack Little, John Markel, Augustine Gray, and others began to develop software tools that would eventually converge with the DSP industry to enable efficient representation of the DSP techniques, and would provide rapid and efficient modeling of these complex algorithms [7, 8].

Meanwhile, the semiconductor industry, continuing to follow Moore's law [9], evolved to the point where the computational performance required to implement digital signal processes used in radio modulation and demodulation were not only practical, but resulted in improved radio communication performance, reliability, flexibility, and increased value to the customer. This meant that analog functions implemented with large discrete components were replaced with digital functions implemented in silicon, and consequently were more producible, less expensive, more reliable, smaller, and of lower power [10].

During this same period, researchers all over the globe explored various techniques to achieve machine learning and related methods for improved machine behavior. Among these were analog threshold logic, which lead to fuzzy logic and neural networks, a field founded by Frank Rosenblatt [11]. Similarly, languages to express knowledge and to understand knowledge databases evolved from list processing (LISP) and Smalltalk and from massive databases with associated probability statistics. Under funding from the Defense Advanced Research Projects Agency (DARPA), many researchers worked diligently on understanding natural language and understanding spoken speech. Among the most successful speech-understanding systems were those developed by Janet and Jim Baker (who subsequently founded Dragon Systems) [12], and Kai Fu Lee et al. [13]. Both of these systems were developed under the mentoring of Raj Reddy at Carnegie Mellon. Today, we see Internet search engines reflecting the advanced state of artificial intelligence (AI).

In networking, DARPA and industrial developers at Xerox, BBN Technologies, IBM, ATT, and Cisco each developed computer-networking techniques, which evolved into the standard Ethernet and Internet we all benefit from today. The Internet Engineering Task Force (IETF), and many wireless-networking researchers continue to evolve networking technologies with a specific focus on making radio networking as ubiquitous as our wired Internet. These researchers are exploring wireless networks that range from access directly via a radio access point to more advanced techniques in which intermediate radio nodes serve as repeaters to forward data packets toward their eventual destination in an ad hoc network topology.

All of these threads come together as we arrive today at the cognitive radio era (see Figure 1.1). Cognitive radios are nearly always applications that sit on top of an SDR, which in turn is implemented largely from digital signal processors and general-purpose processors (GPPs) built in silicon. In many cases, the spectral efficiency and other intelligent support to the user arises by sophisticated networking of many radios to achieve the end behavior, which provides added capability and other benefits to the user.

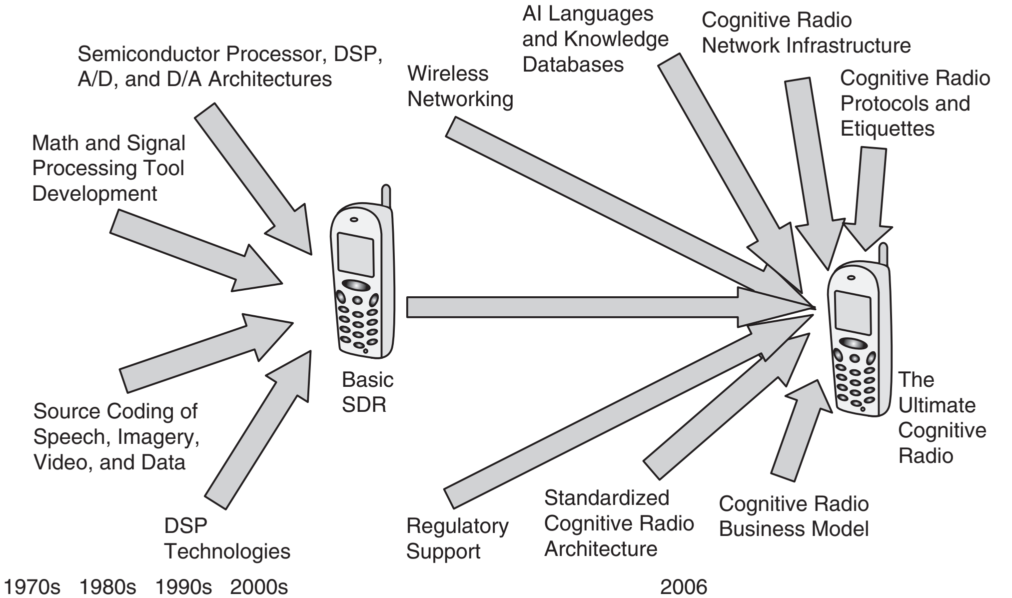

Figure 1.1: Technology timeline. Synergy among many technologies converge to enable the SDR. In turn, the SDR becomes the platform of choice for the cognitive radio.

1.3 A Brief History of SDR

An SDR is a radio in which the properties of carrier frequency, signal bandwidth, modulation, and network access are defined by software. Today's modern SDR also implements any necessary cryptography; forward error correction (FEC) coding; and source coding of voice, video, or data in software as well. As shown in the timeline of Figure 1.2, the roots of SDR design go back to 1987, when Air Force Rome Labs (AFRL) funded the development of a programmable modem as an evolutionary step beyond the architecture of the integrated communications, navigation, and identification architecture (ICNIA). ICNIA was a federated design of multiple radios, that is, a collection of several single-purpose radios in one box.

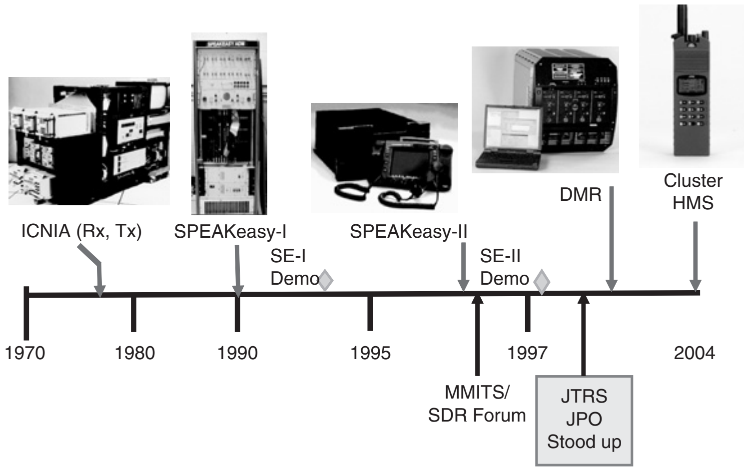

Figure 1.2: SDR timeline. Images of ICNIA, SPEAKeasy I (SE-I), SPEAKeasy II (SE-II), and Digital Modular Ratio (DMR) on their contract award timelines and corresponding demonstrations. These radios are the early evolutionary steps that lead to today's SDR.

Today's SDR, in contrast, is a general-purpose device in which the same radio tuner and processors are used to implement many waveforms at many frequencies. The advantage of this approach is that the equipment is more versatile and cost-effective. Additionally, it can be upgraded with new software for new waveforms and new applications after sale, delivery, and installation. Following the programmable modem, AFRL and DARPA joined forces to fund the SPEAKeasy I and SPEAKeasy II programs.

SPEAKeasy I was a six-foot-tall rack of equipment (not easily portable), but it did demonstrate that a completely software-programmable radio could be built, and included a software-programmable cryptography chip called Cypress, with software cryptography developed by Motorola (subsequently purchased by General Dynamics). SPEAKeasy II was a complete radio packaged in a practical radio size (the size of a stack of two pizza boxes), and was the first SDR to include programmable voice coder (vocoder), and sufficient analog and DSP resources to handle many different kinds of waveforms. It was subsequently tested in field conditions at Ft. Irwin, California, where its ability to handle many waveforms underlined its extreme usefulness, and its construction from standardized commercial off-the-shelf (COTS) components was a very important asset in defense equipment. SPEAKeasy II subsequently evolved into the US Navy's digital modular radio (DMR), becoming a four-channel full duplex SDR, with many waveforms and many modes, able to

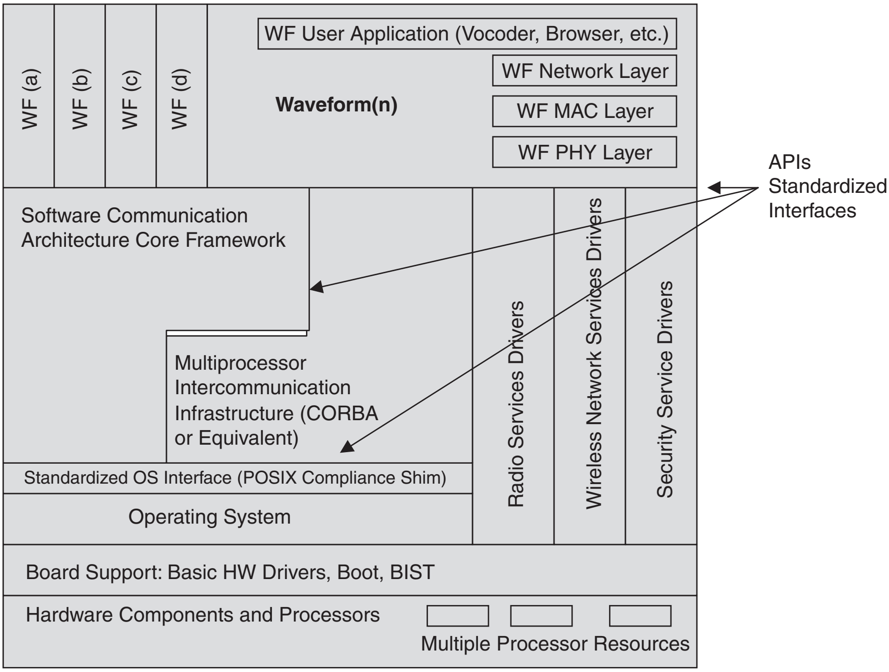

Figure 1.3: Basic software architecture of a modern SDR.[3] Standardized APIs are defined for the major interfaces to assure software portability across many very different hardware platform implementations. The software has the ability to allocate computational resources to specific waveforms. It is normal for an SDR to support many waveforms in order to interface to many networks, and thus to have a library of waveforms and protocols.

be remotely controlled over an Ethernet interface using Simple Network Management Protocol (SNMP).

These SPEAKeasy II and DMR products evolved not only to define these radio waveform features in software, but also to develop an appropriate software architecture to enable porting the software to an arbitrary hardware platform, and thus to achieve hardware independence of the waveform software specification. This critical step allows the hardware to separately evolve its architecture independently from the software, and thus frees the hardware to continue to evolve and improve after delivery of the initial product.

The basic hardware architecture of a modern SDR (Figure 1.3) provides sufficient resources to define the carrier frequency, bandwidth, modulation, any

[3]BIST: built-in self-test; CORBA: Common Object Request Broker Architecture; HW: hardware; MAC: medium access control; OS: operating system; PHY: physical (layer); POSIX: Portable Operating System Interface; WF: waveform.