Cognitive Radio Communications and Networks

Principles and Practice

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CHAPTER

Defining cognitive radio

13

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13.1 INTRODUCTION

Since the early 1990s we observed increasing interest around the world in *cognitive radio* (CR) technology. For example in Figure 13.1, we present the result of a simple web crawl, which shows a monotonic increase in the amount of Internet web pages containing phrases like *cognitive radio*, *dynamic spectrum access*, and *opportunistic spectrum access*. Yet another indication of CR popularity is that, in the past five years, more than 20 books were published, more than 20 journal special issues were arranged, and over 40 conferences organized—all solely dedicated to CR and related concepts (for more detailed information we refer the reader to www.scc41.org/crinfo). However, by closely looking into a random set of recently published papers having CR in their title, we observe that each author has his or her own definition of the topic. For example, hardware specialists have a notion of CR that interrelates to software-defined radio (SDR), while physical layer researchers look at CR with an eye on the bit pipe that can be achieved from the information theory (IT) point of view. Finally, protocol designers look into it from the optimization and implementation perspectives. Not only has there been a lot of ambiguity in CR terminology, almost all interrelated concepts of CR are hitherto defined based on the context. It is then imperative to devote a chapter of this book to clearly understanding all the interpretations of CR and the related concepts.

This chapter is structured as follows. In Section 13.2 we present related terminology that is important to CR. Later, in Section 13.3, we briefly describe the efforts of IEEE to standardize concepts related to CR. The chapter concludes in Section 13.4, while Section 13.5 presents some open questions to the inquisitive reader.

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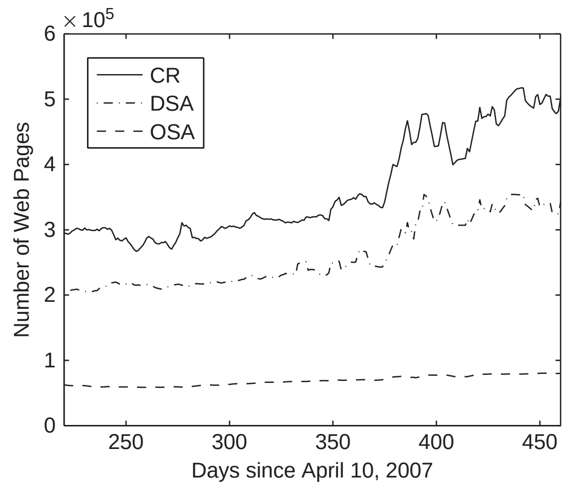

FIGURE 13.1

Statistics of the Google search engine responses for cognitive radio (CR), dynamic spectrum access (DSA), and opportunistic spectrum access (OSA) phrases in terms of number of WWW pages found; see also [544].

13.2 DEFINING CR: HISTORY, APPLICATIONS, AND RELATED CONCEPTS

We can state that the emergence of CR is strongly correlated with contemporary spectrum management that resulted in highly inefficient radio spectrum use. At the core of this problem lies archaic spectrum licensing and management. Such static spectrum assignment, applied to radio frequencies for almost a century, lead to a so-called quasi-scarcity of the spectrum. Therefore, it would be a welcome step if resource-starved users with no license are allowed to utilize dynamically (opportunistically) licensed frequencies when they are free (to minimize interference) at a specific place and time. Such an approach would increase overall frequency reuse and boost the throughput for applications that opportunistically use the empty frequencies.

Many successful attempts have been made in the past to liberalize spectrum access. Before going further with the definition of CR, let us briefly discuss the history of the nonconservation approach to spectrum management.

13.2.1 A Brief History of Elastic Spectrum Management

Looking at the history of radio regulations (especially in the United States), we can find many examples of attempts to liberalize spectrum market. Here, by

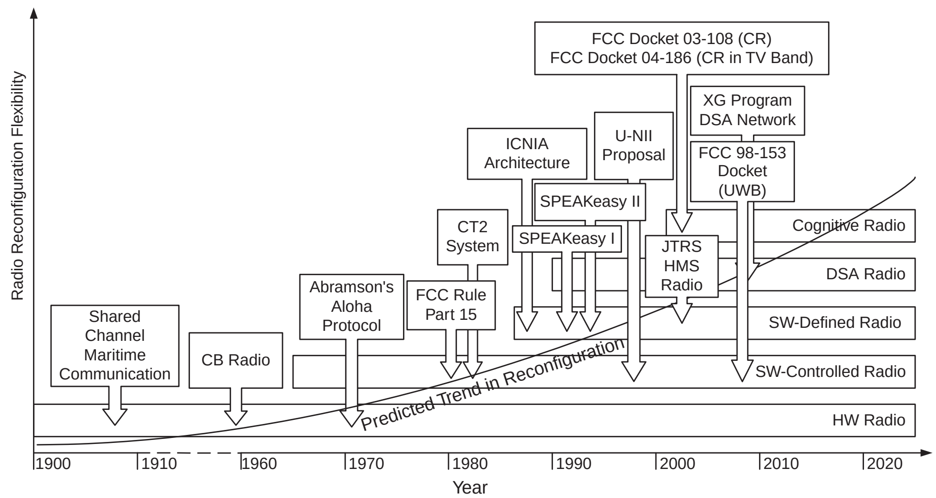

FIGURE 13.2

History of dynamic spectrum access systems and their relation to the implementation platforms, with the view to the future [545]; HW: hardware, SW: software (for the explanation of all other terms the reader is referred to Section 13.2.7).

liberalization, we mean maintaining a set of radio channels to be used by the public without ownership or license. Such maintenance would be completely and spatially distributed (using specific "radio layer management protocols") or supported by a spectrum regulator.

One of the first communication systems with shared radio resources was maritime communication developed in the early 1920s, see Figure 13.2. A 2.182 kHz band was used as an emergency and control channel on which all ships could listen for someone intending to communicate by broadcasting a working carrier identifier for further communication. After World War II, around 1960, the U.S. Federal Communications Commission (FCC) allowed using shared channels in land mobile communication, where one trunking channel could be used by many parties. Basically, hardware extensions like the tone-coded squelch or listen before talk (LBT) were used to share the frequency band. The fact that most transmitted messages were short made the shared channel communication very efficient. In the mid-1970s, the FCC allowed sharing channels at the 27 MHz band (so-called citizen band, CB) on a first-come, first-served basis. The only restriction to the users of the CB bands was to adhere to the maximum transmit power limit.

With innovations in wireless data communication, more flexible ways of spectrum management were possible. Abramson's Aloha protocol, presented first in 1970, was a solution to use radio channels for wireless data communication without a centralized coordinating entity. The ideas of random access were later extended to Packet Radio Networks. This, indirectly, lead to a FCC Rule Part 15, which described the ways of coexistence of low-power wireless devices in the industrial, scientific, and medical (ISM) band. Adopted in 1985, it initially described the methods for wireless devices using spread spectrum as a communication technique. Later, the Part 15 rule was changed to specify any modulation technique that met required power limits, was flexible enough, and contained no "strong spectral lines." Neither etiquette nor LBT protocols were defined in the FCC ruling. Its huge success was later legitimized by FCC's acceptance of the Apple Corp. proposal in 1995 to allow everyone to use the 5 GHz band (called unlicensed-national information infrastructure, U-NII) with no prior license or permission. Currently, U-NII is used with a higher success rate for wireless packet-based communication.

The British cordless telephone second generation (CT2) system, standardized in the mid-1980s, was another example of a successful distributed channel management technique. The 40 MHz band divided into 40 channels was managed by a base station (BS) that could monitor the level of interference on all channels and choose one that possessed minimum interference. CT2 systems were very popular in Hong Kong and Singapore.

George Gilder, in "Auctioning the Airwaves" (published in *Forbes* on April 11, 1994), envisioned that in the future "the wireless systems ... will offer bandwidth on demand and send packets wherever there is room." In parallel, Eli Noam from University of Columbia, proposed, in 1995, an "open spectrum access" paradigm [546], in which interested parties would pay for bandwidth whenever there is demand. Although both proposals addressed no technical issues and were mainly aiming at packet data communication, it was a sign for radio regulators that real steps in liberalizing the spectrum market is the order of the day; that is, it was clearly visible that it might be better to promote licensed parties that share their under- and nonutilized resources. Therefore, in 2002, FCC issued the 98-153 docket, permitting many users to transmit using low-power communication based on ultra wideband (UWB) communication. Recently released FCC docket 03-122 revisited Rule 15, allowing wireless data users to share channels with radar systems on an LBT basis. Finally the FCC realized that CR techniques are the future substrate that stimulate full growth of an "open spectrum" (see FCC Docket 03-108 on CR techniques and FCC Docket 04-186 on CR in TV spectrum). In the second report, FCC 08-260 finally approved allowing the use of TV white spaces in November 2008 (see [63]).

We note that some probes of radio channel liberalization were not so spectacular, mainly due to inflexible rules of operation given by the regulator. Examples of such systems were the radio common carrier (RCC) issued in the mid-1970s, the 800 MHz channel air ground telephone service (AGTS) from the 1990s, the unlicensed personal communications service (UPCS), and the large-scale low-earth orbit satellite system (called *Big LEOS*) with shared code division multiple access (CDMA) channels (early 1990s). First, the RCC could operate only when multiple service providers decided how to share common channels, which was not so financially attractive due to competition among all interested parties. Second, the AGTS was not popular due to the many rules of operation that FCC imposed. Third, the UPCS specification by FCC also included many restrictions to the operation of potential systems. Moreover, it had to share channels with microwave point-to-point links and often spatial separation was necessary between different UPCS devices. Finally, Big LEOS failure was mainly due to the financial problems of the service providers because of licensing fees.

The general idea of CR, as described already, then started to attract lots of attention. Since the introduction of this concept formally in 1999 by Mitola [6], a massive amount of literature has been published on that topic.

A brief illustration of this discussion is given in Figure 13.2. More information on the historical developments in dynamic spectrum management can be found in [547]. Now, given the knowledge of past inflexible spectrum management, we obviously need to look at the future.

13.2.2 A View of Wireless Network Futurists

In the late 1990s, in parallel to what had been happening over the last 100 years in radio spectrum management, a community of researchers, visionaries, futurists, and alike started to think about combining flexible spectrum access concepts with intelligent radio hardware platforms and smart networks. In this framework, emerging paradigms of dynamic spectrum access were related to cognitive communications.[1] The computation abilities of current electronic devices as well as recent developments in computer science and artificial intelligence allowed researchers to start thinking of introducing cognition into wireless networks and devices. This functionality would allow wireless systems in general to become more flexible, inferring from the environment to adapt the internal parameters to fulfill the needs of the user in a better way by taking necessary actions. These intelligent or learning cognitive devices would per se also allow harvesting the radio spectrum more optimally, allowing more users to communicate efficiently without an additional need for licensing. The ultimate dream is to use and reuse the available spectrum to the fullest.

CR can be applied to any communication system or network that suffers from spectrum shortage. It becomes attractive, since it needs no specially designed modulation technique, coding, or the like. We can think of no currently existing network that can be upgraded with such functionality. Ad hoc, sensor, and cellular networks are the ones that might benefit from the additional spectrum capacity it can offer. Operational specific networks can also benefit from the introduction of CR [548]. Moreover, the utility of CR has been recognized by ETSI and considered one of the candidates for the future radio interface of 4G networks. The potential for CR has also been recognized by IEEE. Its growing interest in this research topic is demonstrated by starting an IEEE Communications Society Technical Committee on Cognitive Networks [549]. Furthermore, its newest standard specifies protocols

[1]The term *cognition* is a popular topic in psychological and social sciences, which relates to information processing, understanding, and making sense of observations and using the attained knowledge in future interactions with the environment.

for future regional access networks, called IEEE 802.22, which aim at design of a new radio interface that would harness the so-called TV white spaces. Yet another initiative of the IEEE is a standard related to reconfigurable heterogenous radio interfaces, IEEE 1900.4. More information on the standardization initiatives of IEEE within the framework of OSA is given in Section 13.3.

As pointed out in Section 13.1, during the course of research on CR, there has been a lot of ambiguity in naming certain concepts; that is, different modern approaches of spectrum management were commonly mistaken with CR. We discuss in detail the ambiguous definitions related to CR in Section 13.2.3.

13.2.3 Ambiguity in CR Definitions

Historically, CR was first described in [6,7,329] as a decision-making layer at which "wireless personal digital assistants and the related networks were sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs." This was a vision of an intelligent wireless "black box" with which a user travels. Wherever the user goes, the CR device would adapt to the new environment, allowing the user to always be connected [6]. We need to note that Mitola was not only the creator of the CR notion, he also coined the term *SDR*; see, for example, [329] (we elaborate more on hardware architectures associated with the CR in Section 13.2.7). He thought of CR as a natural extension of SDR, where software allowed the device to flexibly alter transmission and reception parameters to all layers of the communication stack. Also, he was the first one to think of including intelligence ergo cognition to the whole radio setup.

Six years after Mitola's first article on CR, Simon Haykin, in the *IEEE Journal on Selected Areas in Communications* [11], recapitulated the idea of CR. He defined CR as "inclusive of SDR, [an idea] to promote efficient use of spectrum by exploiting the existence of spectrum holes" or an "intelligent wireless communication system ... that adapt(s) to statistical variations in the input stimuli with two primary objectives in mind: highly reliable communication ... [and] efficient utilization of radio spectrum." Thus, he limited the scope of CR to the efficient spectrum utilization-oriented device. His article focuses on signal processing techniques that could be helpful particularly in managing the second goal, efficient utilization of radio spectrum. Not only did he define his own CR, but also altered the basic cognitive cycle proposed by Mitola [329]. This article [11] was the first major article to give a totally different definition of CR and at the same time introduce terminology confusion. Interestingly, according to Google Scholar, as of September 30, 2008, the original Mitola paper on CR [329] was cited 404 times, while Haykin's paper [11] was cited 669 times!

Not only researchers but also regulatory bodies and standardization institutions defined CR in their own ways, more often than not self-serving. For example, SDR Forum explains CR is "a radio that has, in some sense, 1) awareness of changes in its environment and 2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimize a loss in performance."

In contrast to these definitions, the FCC describes CR as a wireless node or network able to negotiate cooperatively with other users to enable more efficient utilization of radio resources; see FCC Docket 03-108 and 03-186 for a more detailed description. CR would be able to identify a portion of the unused spectrum and utilize it for communication purposes. Thus, just like in Haykin's paper [11], the FCC's approach is a simplified form of Mitola and Maguire's vision where only radio spectrum conditions are considered while making a decision about future transmission and reception parameters. We can thus conclude that the original CR concept of Mitola is limited in scope in the later literature, purely to a radio that efficiently utilizes spectrum, looks for spectrum opportunities, and its adaptation process is limited to the physical layer.

Yet another notion of CR can be found in the IT community. Chapter 11 of this book is mainly devoted to the discussion of CR in an IT context. There, CR is limited to analysis of capacity and throughput of tx-rx Pair 1 (in that context called *secondary users*) with tx-rx Pair 2 (called *primary users*) that interferes with Pair 1. In this context a notion of *cognitive channel* is presented; that is, a channel in which a secondary pair of nodes possesses some kind of side information on what actually the interferer is transmitting. It is clearly seen that cognition in an IT context is far different from what Mitola expressed as "cognition." We can see that many of these approaches have different ideas and goals. Using the preceding CR explanations, some important aspects are sieved and Table 13.1 tries to consolidate them.

Luckily, some institutions aim at standardizing CR-related concepts and give them back their original meaning. One of the firsts and currently the major one

Table 13.1 A Coarse Comparison of Different Interpretations of CR

Aspects	Mitola	Haykin	SDR Forum	FCC	Inf. Theory
User's needs	✓				
Context	✓				
Intellig. & contr.	✓	✓	✓		
Radio/spectr.	✓	✓	✓	✓	✓
Spectr. effic.		✓	✓	✓	✓
Primary users		✓	✓	✓	✓
SDR	✓	✓			
Cooperation				✓	
Reliability		✓			

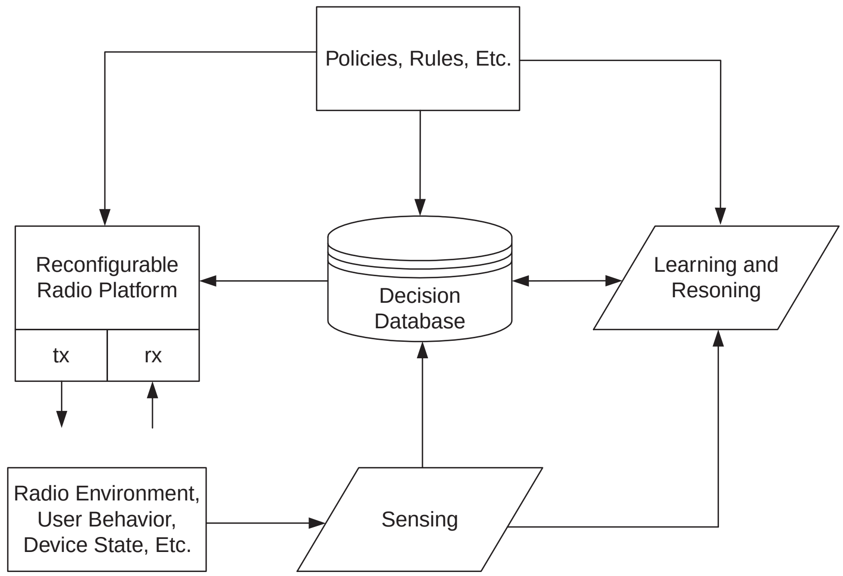

FIGURE 13.3

Components of a CR node, see also [545].

is the IEEE Standard Coordination Committee 41 (IEEE SCC41) (more information on the work of IEEE SCC41 is given in Section 13.3). One of the working groups of IEEE SCC41, IEEE 1900.1, was constituted solely for the purpose of gathering all the definitions that accompany CR. In the IEEE 1900.1 standard [550], the cognitive functionality may be spread across the layers of the communication architecture, resulting in coordination among the layers for an efficient use of the available spectrum. Figure 13.3 explains the basic functional blocks of such a CR node. Specifically, apart from a reconfigurable radio, a CR node has various components. The sensing and policies block (if available) are extensively used in deciding the availability of spectrum. These blocks also help in driving the learning and reasoning functions. The decision database, along with the input from the sensing and policies, block drive learning. The result is that the radio is configured based on input from different layers of the communication stack as well as from the environment inputs.

Moreover, recent research papers outline the possibility of extending the principle of cognition to the entire heterogeneous networks, thus defining the concept of cognitive networks (CNs) [326]. The aim of CNs is to self-adapt to changing requirements from users' applications to provide quality of service and self-management capability. Such a networking paradigm is based on the availability of software-adaptable network elements, driven and configured by a cognitive process. A cognitive process is a decision-making engine in which decisions are based on the current network conditions and involve adaptation and learning techniques. It is important to note that the concept of CN originated independently from the concept of CR.

We also need to emphasize that there is yet another ambiguity in the definition of CN, since we cannot equate CN and cognitive radio network (CRN). Referring again to Chapter 11 of this book, for example, CN is defined as a network constructed of primary and secondary users (we define these concepts later in Section 13.2.6), where secondary users are considered the cognitive ones. These users simply obtain the additional information on the activity of the primary users to employ better transmission parameters, in this context limited only to coding.

13.2.4 A Glossary of Cognitive Radio Definitions

Presented here is a *figurative* glossary of definitions—and some of them paraphrased from different sources and put together for easy comparison. This should also aid in getting a complete idea of what other researchers are thinking. We refer interested readers to the original texts and articles for more explanations and details.

Mitola [6, 7, 329]. Wireless personal digital assistants and the related networks that are sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context and to provide radio resources and wireless services most appropriate to those needs.

Wikipedia. Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently, avoiding interference with licensed or unlicensed users. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behavior, and network state.

IEEE 1900.1 [550]. (a) A type of radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives; (b) cognitive radio [as defined in item a] that uses software-defined radio, adaptive radio, and other technologies to adjust automatically its behavior or operations to achieve desired objectives.

Haykin [11]. Cognitive radio is an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding by building to learn from the environment and adapt to statistical variations in the input stimuli to achieve high reliability and efficient utilization of the radio spectrum.

Scientific American [551]. Cognitive radio is an emerging smart wireless communications technology that will be able to find and connect with any nearby open radio frequency to best serve the user. Therefore, a cognitive radio should be able to switch from a band of the radio spectrum that is blocked by interference to a free one to complete a transmission link, a capability that is particularly important in an emergency.

Rondeau and Bostian [552]. Cognitive radio is a system that has a cognitive engine performing modeling, learning, and optimizing the processes to reconfigure the communication system including the radio layer by taking the information from users, radio, and the context.

13.2.5 A Generalized Definition of Cognitive Radio Network

An interesting aspect we observe with respect to CR is that it fits many fields of scientific and engineering endeavors. For example, it stimulates signal processing techniques with respect to detection and sensing; it looks like a fertile area of application for artificial intelligence (AI); it encourages estimation theory enthusiasts as well as linguists with respect to policy language; it provides new creative opportunities for systems specialists.

To conclude, here we define the CR—in layman's terms—as the concept with which the wireless nodes adapt their properties, including radio, to achieve overall efficient spectrum usage, in time and space, based on the factors such as radio, radio environment, policies, and higher-layer requirements with an inherent and constant learning to improve the spectrum usage.

13.2.6 Concepts Related to Spectrum Management

In the previous section we conclude that CR has been somehow reduced to the spectrum management layer only. Thus, all the concepts related to modern approaches in spectrum management are again mixed with CR [109, 545, 553]. To clear the ambiguity in terminology let us briefly introduce our classification in Figure 13.4.

We can consider three essential models: *exclusive spectrum management* (ESM), the *spectrum commons* (SC) sharing model, and *hierarchical spectrum management* (HSM). The ESM model still gives exclusive channel usage to each user or service provider but differs from a static assignment in the sense that the channels are allocated dynamically among possible licensees. The process of exclusive channel access is usually governed by radio regulation bodies. The differences between ESM approaches, specified in Figure 13.4, depend on the economic model, which varies from country to country. In the SC model, different users compete for the assigned frequencies on equal terms. The HSM model gives *primary (licensed) users* (PUs) more rights to use the spectrum than other *secondary (unlicensed) users* (SUs). We can distinguish two HSM approaches. In *overlay* HSM, only one user/system can use a frequency band at a particular space and time, and the SUs have to back off when a PU is present. However, when no PU is present, the SU can opportunistically use the frequency band, so this technique is also referred to as *opportunistic spectrum access*. In *underlay* HSM, an SU can transmit on an

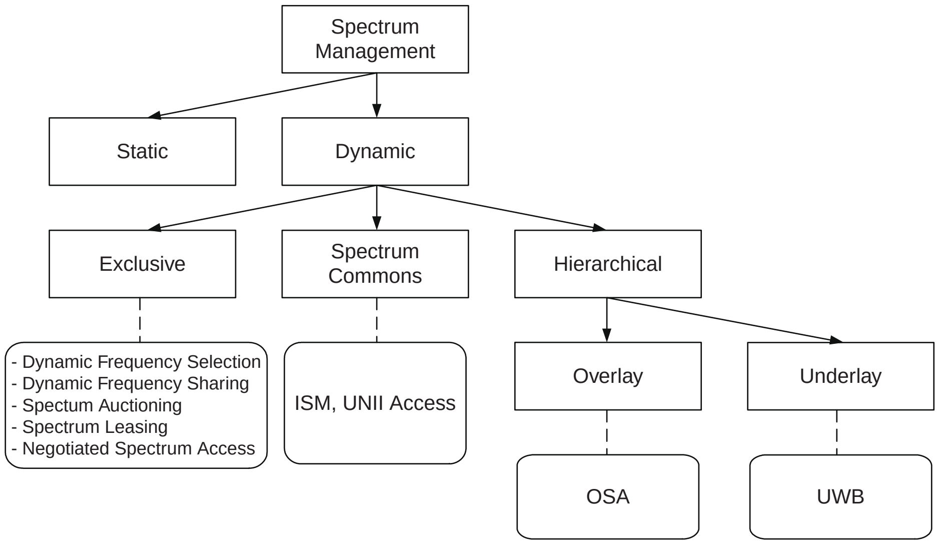

FIGURE 13.4

Modern spectrum management: classification with the application examples. See also [109, 553, 554].

already occupied band if this transmission does not increase the interference to the PU above a given threshold. A further classification of overlay HSM (not shown in Figure 13.4) involves *symmetric coexistence* (when both SU and PU networks adapt) and *asymmetric coexistence* (when only the SU network adapts, obeying the PU requirements).

13.2.7 Concepts Related to Computational Platforms

Yet another definition ambiguity comes from the CR implementation. Categories and classes of different future adaptive radio devices are listed in Table 13.2. This simplistic comparison tries to show the differences among them, since some confusion still persists in the CR community on how to classify different devices and systems. Please note that in Figure 13.2 different milestones in spectrum management flexibility have been mapped into different hardware platforms. The more flexible the given system is, the more flexible the hardware platform becomes. Certain milestones that we have to note in developing software-based radio platforms are SPEAKeasy [555], joint tactical radio system [556], DARPA XG program radios [557], and integrated communications, navigation, identification avionics (ICNIA) [558]. We can predict semi-exponential growth in hardware flexibility in the coming years (see again Figure 13.2).

Some explanations and features of the terms in Table 13.2 follow. We refer to the SCC41 1900.1 standard for very detailed descriptions of many of these terms and their interrelationships [550].

Table 13.2 Types of Adaptable Radio Devices (HW: Hardware, SW: Software)

Type of Radio	Platform	Reconfiguration	Intelligence
Hardware	HW	Minimal	None
Software	HW/SW	Automatic	Minimal
Adaptive	HW/SW	Automatic/predefined	Minimal/none
Reconfigurable	HW/SW	Manual/predefined	Minimal/none
Policy based	HW/SW	Manual (database)/ automatic	Minimal/none
Cognitive	HW/SW	Full	Artificial/ machine learning
Intelligent	HW/SW	Full	Machine learning/ predicting decision

Hardware radio. The capability of CR devices changing their radio characteristics is implemented completely in hardware. Thus, once in the field the devices will not be able to change their characteristics other than what is already built in. For example, the range of frequency programmed into the hardware always remains the same, even though the user knows that there is an opportunity to work in a different range. Therefore, the scope is limited in this case.

Software radio. The capability of CR devices changing their radio characteristics also is implemented in software. Thus, the devices are able to change their characteristics from other than what is already built in. For example, contrasting with the preceding, the range of frequency programmed into the hardware may be changed by uploading a new software patch (say, a simple configuration file).

Adaptive radio. This is the capability of CR devices where its radio characteristics are changed by mechanisms such as closed-loop or open-loop controllers. Basically, the devices adapt to the surroundings by sensing and using the preprogrammed logic and control techniques.

Reconfigurable radio. The radios in CR devices of which the functionalities can be changed manually. A hardware radio and a software radio both are reconfigurable, though in different ways and to different degrees.

Policy-based radio. The changes to the radio functionalities of CR devices are governed by the policies. The policy set usually is available as a data set (or database). For example, the frequencies used by military equipment are not allowed to be used by others under all circumstances. Basically the policy set governs the operational characteristics of the CR devices quite immaterial of whether they are capable.

Cognitive radio. It has been already defined. This includes databases, policies, learning techniques, and so forth.

Intelligent radio. This includes cognitive radios, which are also able to learn as well as predict the situations and adapt themselves. In a general and crude sense, it is a software radio. However, with respect to the previous explanation of the software radio, it just specifies the capability to work with a software control, thus an intelligent radio is much more than a simple software radio.

13.3 CR TERMINOLOGY STANDARDIZATION

In today's world of information and communication technology (ICT), specific themes require tight and efficient interaction between research and standardization efforts to enable new technologies to flourish and reach maturity. In the area of CR, IEEE SCC41 is a coordination body within the IEEE standardization organization "in the areas of dynamic spectrum access, cognitive radio, interference management, coordination of wireless systems, advanced spectrum management, and policy languages for next generation radio systems." Based on a summary of the IEEE SCC41 structure from [545, 559] we provide additional information on the recent developments within the project.

13.3.1 General Overview

The IEEE SCC41 effort was preceded by the IEEE P1900 Standards Committee, jointly sponsored by the IEEE Communications Society (ComSoc) and the IEEE Electromagnetic Compatibility (EMC) Society. The objective of P1900 was to develop supporting standards dealing with new technologies for the next-generation radio and advanced spectrum management. Keeping an eye on the broad spectrum of required technologies for the emerging wireless communications, the IEEE Standards Board constituted reorganization of the IEEE 1900 effort as IEEE SCC41 "Dynamic Spectrum Access Networks" (DySPAN). Thus, IEEE SCC41 oversaw a range of new standards that aid in the speedy development of the technology for next-generation wireless networks. Within the IEEE, SCC41 is a direct sponsor of standards, reporting directly to the IEEE Standards Board. The IEEE 1900 committee ceased to exist at the inaugural meeting of IEEE SCC41 in April 2007 during the IEEE DysPAN Conference. The work of all IEEE P1900 working groups continued under IEEE SCC41, retaining the same names as before. A brief diagrammatic representation of various working groups is represented in Figure 13.5.

The activities of IEEE SCC41 are supported by IEEE Communication Society technical committees, which represent the interface with the research community in terms of proposals for new standards and technical contributions to the internal discussions within the working groups (WGs). At the time of writing, this chapter IEEE SCC41 had six WGs, each responsible for evolving standardization processes for different aspects of DSA. WGs are identified as IEEE 1900.x, where .x represents one of the WGs. Each WG submits its evolved standard document to IEEE after

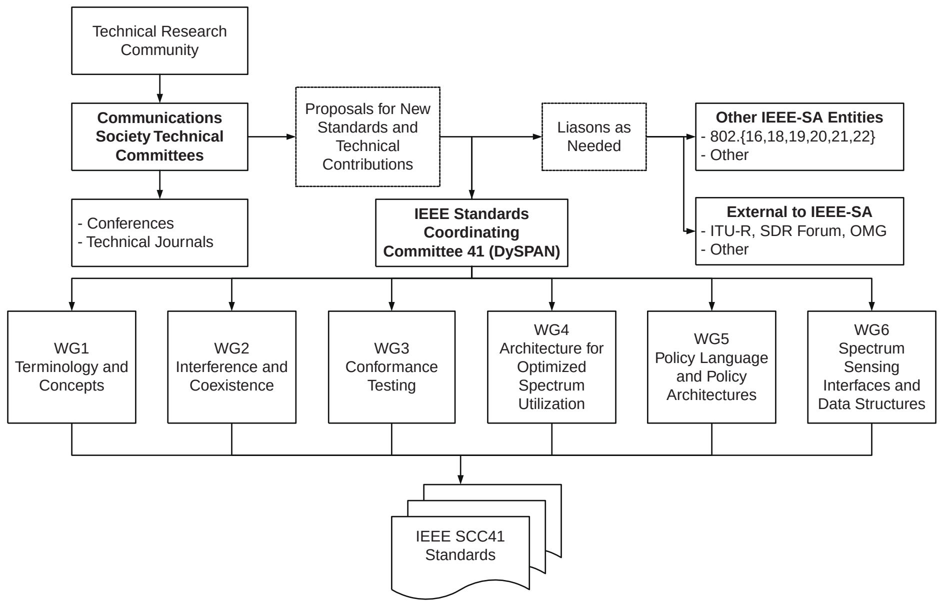

FIGURE 13.5

IEEE SCC41 organization structure and relationships with other entities. See also [545, Fig. 2].

finalizing the recommendations through discussions. The WG first prepares the document, which is open to all the IEEE Standard Association (SA) members as well as outsiders (on a fee-per-vote basis). Once the voting members are identified and the documents finalized, the documents go for ballots arranged by the IEEE SA. During the balloting, IEEE SA members vote with their comments. Negative votes are carefully considered by the working group and the issues addressed by them go into the next round of discussions, rewriting, and balloting. Thus, a fair chance is given to interested organizations and individuals to make the standards applicable to a wide spectrum of products using dynamic or opportunistic spectrum access. This process can be repeated many times, depending on the comments and attention a standard document invokes. Now we briefly explain the scope of each WG in the sequel.

13.3.2 IEEE 1900.1

As we point out in Section 13.2 many groups working on CR have defined CR and other related terms differently. Thus, IEEE decided to create 1900.1 WG, Standard Definitions and Concepts for Spectrum Management and Advanced Radio System Technologies, responsible for creating a glossary of important CR-oriented terms and concepts. It further provides explanations to germinate a coherent view of the various efforts taking place in the broad arena of CR. The key idea was to standardize and prepare technically precise definitions related to CR. In fact, 1900.1 WG acted as a glue to the other IEEE SCC41 WGs, tying them together with common definitions of CR terms. The IEEE 1900.1 has been voted by the IEEE Standard Association and is a standard now.

13.3.3 IEEE 1900.2

In light of new CR technology, many radio systems coexist and they try to optimize the utilization of spectrum in space and time. The accurate measurement of interference has thus become a crucial requirement for the deployment of these technologies. The mandate of the 1900.2 WG, Recommended Practice for Interference and Coexistence Analysis, was to recommend the interference analysis criteria and establish a well-thought-out framework for measuring and analyzing the interference between radio systems. New technologies, while attempting to improve spectral efficiency—by being flexible, collaborative, and adaptive—also cause disputes. Therefore, this WG established a common standard platform on which the disputing parties can present their cases and resolve them amicably.

The framework for interference analysis addresses the context of measurements and the purpose. Any new adaptive system has a trade-off between cost and gain. Therefore, the interference analysis should make this gain explicit, along with the usage model for this trade-off. Apart from the interference power measurements and the context, impact and remedies are also mentioned for analysis and comparison. Finally, parameters for analysis are derived from scenarios including the context and harmful interference thresholds. Uncertainty levels in measurements are compulsorily considered in the analysis. Just like 1900.1, the 1900.2 has been voted by IEEE Standard Association and has become a standard.

13.3.4 IEEE 1900.3

On the software front, IEEE 1900.3 WG, Recommended Practice for Conformance Evaluation of Software-Defined Radio Software Modules, is developing test methods for conformance evaluation of software for SDR devices. The aim is to define a set of recommendations that helps in assuring the coexistence and compliance of the software modules of CR devices before proceeding toward validation and certification of the final devices, as laid down in IEEE 1900.2. Since SDR is an important component of future CR networks, these recommended practices should help in creating high confidence in the deployed SDR devices. These devices will have multiple layers of software, each addressing different functionalities. Therefore, it is all the more essential to test the capability of SDR devices a priori to install the patches correctly over the air, assuring secure execution of intended functionalities.

As an illustration consider an implementation of the SDR device specifications into a program. This can be verified with the formal verification methods. However, formal specifications for software, mostly, do not exist. Therefore, testing in these cases becomes less formal, by focusing on only a particular subset of device operations. The aim is to design testing procedures that will comply with the semi-formal software specifications. One of the solutions is to define checkpoints (mandatory or obligatory) and assertions that will reflect the specifications. For these reasons IEEE 1900.3 WG specifies device management procedures. Since many of those exist today (e.g., Java's Mobile Device Management Server application programming interfaces), 1900.3 WG utilizes other relevant standards to achieve its goal.

13.3.5 IEEE 1900.4

Many mobile devices used today operate on multiple wireless networks. The study of network and device architectures that can help in distributed decision making for DSA is an important area, commercially as well as academically. These procedures particularly refer to reconfigurable terminals (including SDR) capable of accessing a multitude of radio access technologies. The 1900.4 WG, Coexistence Support for Reconfigurable, Heterogeneous Air Interfaces, defines the overall system architecture, splitting the functionality between terminals and the network, and the information exchange between coordinating entities. Its main goal is to increase the overall system utilization of reconfigurable terminals while increasing the perceived quality of service. All 1900.4-enabled devices should operate in an OSA or DSA manner so that they will not degrade the performance of PU radio access devices. The study of heterogeneity in wireless access technologies and multihoming of the devices—with CR capability—differentiates this WG from other WGs of SCC41. At first the 1900.4 WG looks into only the architectural and functional definitions. The corresponding protocol definitions related to the information exchange are addressed at a later stage. This standard was approved in late January 2009. After the successful work and much interest in this WG, two more projects have been assigned to 1900.4 WG:

1900.4a. Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks—Amendment: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands.

1900.4.1. Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks.

With these two projects, the scope of 1900.4 has expanded IEEE's interest in the community.

13.3.6 IEEE 1900.5

The recent WG of IEEE SCC41, started in August 2008, on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access

Applications, defines a policy language (or a set of policy languages or dialects) to specify interoperable, vendor-independent control of CR functionality and behavior for DSA resources and services. The initial work concentrates on standardizing the features necessary for a policy language to be bound to one or more policy architectures to specify and orchestrate the functionality and behavior of CR features for DSA applications (see www.scc41.org/5).

13.3.7 IEEE 1900.6

Yet another WG of IEEE SCC41 started in August 2008, on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and Other Advanced Radio Communication Systems. The intended standard defines the information exchange between spectrum sensors and their clients in radio communication systems. The logical interface and supporting data structures used for information exchange are defined abstractly without constraining the sensing technology, client design, or data link between sensors and clients (see www.scc41org/6).

13.3.8 Related Standardization Efforts

Other IEEE projects related to next-generation radio, like IEEE 802.{18, 19, 20, 22} are the sources of expertise for IEEE SCC41. As mentioned earlier, since active dialog between different standard bodies is crucial at this stage of CR development, IEEE SCC41 initiated cooperation with the FCC, Ofcom, SDR Forum, and OMG Forum, to name a few. The relation between different WGs of IEEE SCC41 as well as different standardization bodies within and outside IEEE are depicted in Figure 13.5.

IEEE 802.22 for TV White Space

To make universal broadband access a reality, allow the Internet service industry to grow, and make consumer Internet access competitive by providing more choices, the TV white space was opened for unlicensed use by the FCC [63]. Thus, the ubiquitous use of wireless access is thought of as a major deciding factor to allow more spectrum. In fact, even a fixed wireless access has many advantages over wired network access in terms of ease of setting up and use. In this direction, the white space coalition is one such initiative that influenced the FCC to open up the TV spectrum. Further, IEEE 802.22 indeed took the initiative to define a standard to use TV white space.

IEEE 802.22 is thought of as an alternative technology to WiFi with an unlicensed spectrum like that of WiFi, but a better spectrum between 54 MHz and 863 MHz. Similar to TV signals the access to Internet could be over tens of kilometers and no restrictions regarding in-building environments and the like. However, the challenges were many: identification of the primary users, listing the unused channels locally, and defining the power levels so as not to interfere with the adjacent bands. The two important entities defined here are the base station and customer premises equipment (CPE). BS controls all the CPEs, determining when to send data and the channels to use. CPEs also sense the spectrum in its vicinity, enabling distributed sensing, and send it back to the BS. With the opening up of TV white space by the FCC, this standard gained a significant role. We refer the reader to Chapter **??** of this book for a detailed description of this standard.

13.3.9 Results and Roadmap of IEEE SCC41

IEEE SCC41 and its previous avatar, IEEE P1900, successfully took steps toward the standardization process of the class of CR systems, spectrum agile systems, dynamic and opportunistic spectrum sharing systems, and their usage paradigms. The current results include an approved standard of 1900.1, 1900.2, and 1900.4.

Notwithstanding the work in these WGs, IEEE SCC41 took a new initiative to invite more projects and potentially set up new study groups (SGs). In case an SG successfully demonstrates the relevance of an issue to the goals of IEEE SCC41, it could submit a request to constitute a new WG and work toward the development of a new standard. As an example, recently, IEEE SCC41 received proposals for the standardization of requirements for disaster recovery, representation of information exchange in CR systems, and detection of primary users.

Indeed, IEEE SCC41 is actively working as an incubator and an "umbrella" for supporting, facilitating, and encouraging the efforts for standardization of the multifaceted issues of cognitive communications. For interested readers we list here some open issues for standardization that will expedite the proliferation of CR:

Regulatory. There are some issues concerning regulatory aspects that are not addressed by the current WGs. Though 1900.2 is addressing some of the dependability concerns, it is not complete at this time. Issues such as priority among various users, interference caused to primary and secondaries, measurement of interference, and detection and dependability detection are some of them.

Test procedures. It is surmised that CR devices will have to go through multiple tests. It is not just the interference caused, but an important question is how to quantify the intelligence. Hence, there is a need to standardize the metrics that would also boost efficient spectrum usage.

Protocols. Protocols with respect to the use of CR methodology need to be addressed in a prominent way. Some of the issues are integrating with OSI-layered architecture, protocols to exchange data, MAC protocols to increase the use of white space, and protocols that assure dependability.

Interoperability. Coexistence and cooperation are the hallmarks of CR devices. Many shades of CR stacks are surmised to be developed in the near future. If CR is going to enhance spectrum reuse, then these devices with different approaches need to meet at some point. They need to operate together. A standard way of doing this is needed.

Medium access control. Medium access control (MAC) protocols, particularly distributed MAC for ad hoc networks operating in the opportunistic spectrum, are not covered by any standard yet. Intelligent spectrum management such as

IEEE 802.11k covers only the unlicensed bands. There is a need for a generalized CR-MAC, defined for CR, that takes into account many of the specificities of CR. It is envisaged that many future versions of MAC inherit this generalized CR-MAC, and it requires sufficient generalization and flexibility.

Security. The standards should define the security apparatus for CRs. The enforcing agencies need such standards to nail down the devices that violate these features. It is in fact very important, since the devices are supposed to be adaptive and intelligent. The need is to develop a standard to (a) detect infringement and (b) enforce fairness. Authorization, avoiding denial-of-service attacks, and resilience to intruders are some issues important here.

13.4 CHAPTER SUMMARY

This chapter provides a terminology foundation for conceptualizing CR. It also provides discussions on difficulties in defining CR unambiguously. An explanation is given regarding the reasons why the community faces such a situation. A clear definition of CR is presented and a historical perspective of CR is also given. Moreover, most important definitions, which are interrelated to CR but hitherto used imprecisely, are also presented. Finally, this chapter discusses briefly the efforts of IEEE to standardize all concepts important to CR.

13.5 PROBLEMS

1. Are there any lessons learned from the initial "terminology mess" related to CR? Is there a way to avoid multiple interpretations of research terms? Or is it a natural research process, presumably on novel system-level concepts, mixing different notions? Discuss.
2. Give examples for each platform listed in Table 13.2.
3. Think of any other term related to CR. Does the CR community need more terms to describe its work or is the descriptive process complete? Provide justification for your statements.
4. Enhance Figure 13.2 with the help of recent literature on this topic.
5. Discuss the future of CR as a technology for the development of new applications.
6. It is envisaged that CR devices will be part of a communication stack in the near future. However, the legacy networks will not be able to cooperate and work with the new CR devices. Discuss possible ways to circumvent this problem.

7 Define *spectrum efficiency* under CR. How is spectrum efficiency dependent on the various aspects of CR?

8 Cognition is a key aspect in CRs; therefore, where would you keep "cognition"? Assuming that you are using the formalism of an OSI stack, where can cognition be placed? Can cognition be distributed?

9 Make a case study of an emergency network and explain how CR can aid the first responders.

10 Explain with reasoning why CRN will be the way to the next-generation communication networks.