IEEE Standards Supporting Cognitive Radio and Networks, Dynamic Spectrum Access, and Coexistence

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ABSTRACT

Cognitive radio techniques are being applied to many different communications systems. They hold promise for increasing utilization of radio frequencies that are underutilized today, allowing for improved commercial data services, and allowing for new emergency and military communications services [1]. For example, these techniques are being considered by the U.S. FCC for communications services in unlicensed VHF and UHF TV bands. Although traditionally these techniques are closely associated with software-defined radios, many standards such as WiFi (IEEE 802.11), Zigbee (IEEE 802.15.4), and WiMAX (IEEE 802.16) already include some degree of CR technology today. Further advances are occurring rapidly. IEEE 802.22 will be the first cognitive radio-based international standard with tangible frequency bands for its operation. Standardization is at the core of the current and future success of cognitive radio. Industry stakeholders are participating in international standards activities governing the use of cognitive radio techniques for dynamic spectrum access and coexistence, next-generation radio and spectrum management, and interoperability in infrastructure-less wireless networks. This article provides a review of standardization activities for cognitive radio technologies and comments on prospects and issues for future standardization.

INTRODUCTION

Technology forecasts predict that cognitive radio (CR) will be a critical part of many future radio systems and networks. Some regulatory domains, such as the Federal Communications Commission (FCC) in the United States and Ofcom in the United Kingdom, already are considering the use of CR technologies [2, 3]. A great deal of effort is pouring into cognitive radio technology and standards but is scattered across many activities. Several standardization organizations such as the Software-Defined Radio (SDR) Forum and International Telecommunications Union-Radio Sector (ITU-R) are working in this area [4]. This article surveys those activities within the IEEE.

The IEEE has two well-known standards activities in this area — SCC41 (formerly known as P1900) and IEEE 802.22. However, there are several other, lesser known, related activities within IEEE as well. Before reviewing these, we present some background on cognitive radio and related technologies.

The term cognitive radio first was used publicly in an article by Joseph Mitola III, where it was defined as

"The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs." [5]

The definition was developed in the context of a software-defined radio (SDR), where the radio could easily be reconfigured to operate on different frequencies with different protocols by software reprogramming. Later the term was reused and reworked to suit different requirements by different authors. The level of cognition attributed to a radio depends on the complexity and intelligence of its cognitive engine, which can have learning capabilities and make decisions based on real-time changes in the operating conditions of the radio. Today, the term cognitive radio generally refers to a radio system that has the ability to sense its radio frequency (RF) environment and modify its spectrum usage based on what it detects. Note that the use of the term *system* is intentional as the components of a cognitive radio system can be distributed across multiple protocol layers and devices in a network. Often the term system is

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implicit when the words cognitive radio are used, but they are made explicit here for clarity. The specific behavior described in this paragraph also is termed *dynamic spectrum access* or DSA.

Figure 1 provides a high-level view of the components that can be found in a cognitive radio system. Minimally, there must be at least one reconfigurable radio component with parameters, such as operating frequency and bandwidth, although many more parameters may exist. A sensing engine must exist that may accept inputs from the radio components, but many other sources also can be present, such as other networked nodes or data sources on the Internet and data such as geolocation data. The system can have a policy database that determines what behavior is acceptable in what circumstances. This database can be dynamically configurable allowing for policy changes. The system must have a reasoning engine that accepts inputs from the sensing engine and a policy database that determines an appropriate configuration for the radio components. The reasoning engine can be capable of learning, based on experience. Finally, a configuration database would maintain the current configuration of the radio components. A simple CR system might have a single reconfigurable radio component accepting sensing information from a single local node and no external data sources.

Within IEEE, an area known as *coexistence*, which is indirectly related to cognitive radio, has been considered for many years. Many radios must include an ability to *coexist* with other radios using different protocols in the same bands. This is particularly true in unlicensed bands where a wide variety of unrelated protocols are applied, including such IEEE standards as IEEE 802.11, IEEE 802.15, and IEEE 802.16. In particular, techniques such as dynamic frequency selection (DFS) and power control (PC) were developed and standardized to deal with coexistence issues. The coexistence techniques developed and being developed for these bands are similar to those for DSA. In some regards, the application of CR/DSA techniques can be thought of as an evolution of coexistence techniques.

Figure 2 shows a timeline for the evolution of cognitive standards within IEEE that takes coexistence standards as a starting point. Initial coexistence standards provided methods of measuring interference and mitigating interference through manual coordination. Human beings provided the cognitive engine! This can be thought of as a first generation of coexistence standards. These standards started being developed as early as 1999. Eventually people realized many of these techniques could be automated, and a second generation of standards resulted, including capabilities such as DFS and PC. Today CR/DSA standards are being developed that address issues such as coexistence. The specific standards and their timelines are depicted in Fig. 2.

In unlicensed frequency bands, coexisting protocols often have equal status and share equally. But the most important application of CR today is for *secondary users*, who can use only certain bands on the condition that they do not disturb the *primary users* of licensed bands. A spectrum shortage often is perceived (particularly at lower frequencies) because the entire spectrum has been allocated to primary users. Yet it has been found that in different geographic locations, large segments of the allocated spectrum are not utilized. (See, for example, [6].) CR/DSA techniques can permit additional (secondary) use of spectrum while protecting primary users. Many applications for CR technology exist, but minimally include commercial data networks, emergency services networks (first responders), and military networks. These applications of CR/DSA techniques still can be viewed as coexistence.

As with many networking technologies, it is important that standards be developed for cognitive radio and applications such as coexistence. A great deal of standardization work has been conducted in recent years, and more work is in progress. This article reviews that work and is organized as follows: we consider the standards already developed or in development today that relate to CR technology. We discuss possible future directions. We summarize this article.

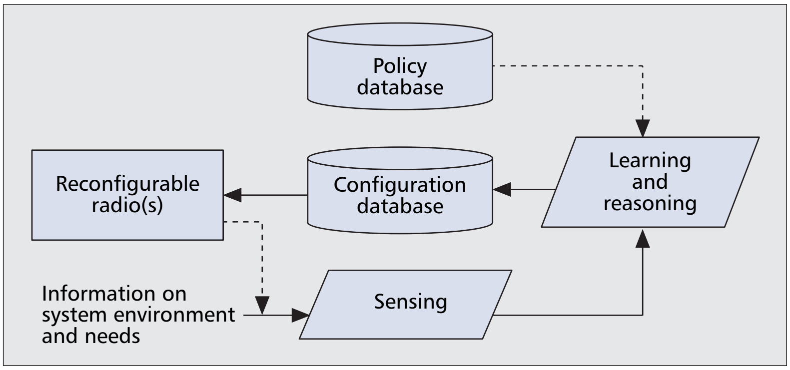


Figure 1. *A view of the components that may exist in a cognitive radio system.*

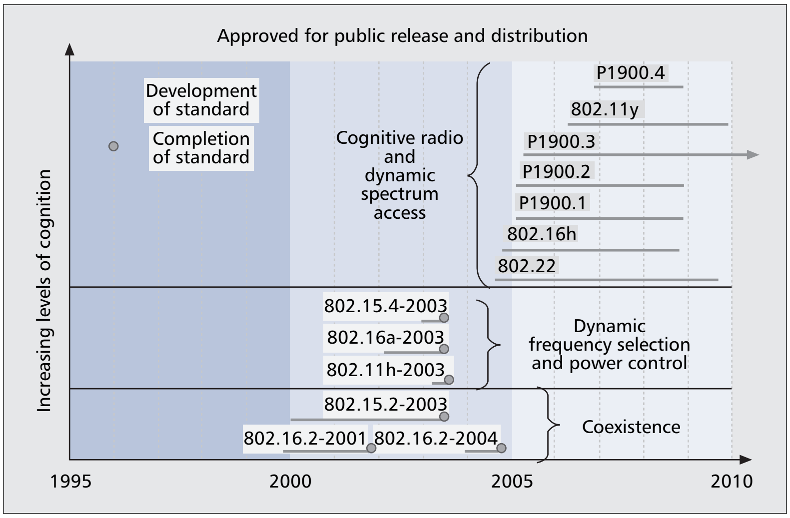


Figure 2. *The evolution of IEEE standardization activities relating to dynamic spectrum access starting with coexistence standards, evolving toward DFS/PC, and finally encompassing true CR/DSA techniques.*

Cognitive Radio and Related Standards Activities

Tables 1–3 provide a synopsis of standardization work that was or is being conducted within IEEE for CR and related technologies. Table 1 pre-

Standard	Scope
802.16.2-2001 Initiation: 9/1999 Completion: 11/2001	One of the first coexistence standards, this recommended practice provided guidelines for minimizing interference in fixed broadband wireless access (BWA) systems. It addressed pertinent coexistence issues and recommended engineering practices, as well as provided guidance for system design, deployment, coordination, and frequency usage. It covered frequencies of 10 to 66 GHz frequencies in general, but focused on 23.5 to 43.5 GHz. It has been superseded by 802.16.2-2004.
IEEE 802.15.2-2003 Initiation: 1/2000 Completion: 6/2003	This standard provides recommended practices for coexistence of IEEE 802.15™ wireless personal area networks (WPAN) with other selected wireless devices operating in unlicensed frequency bands. It suggests recommended practices for IEEE Std. 802.11™, 1999 edition devices to facilitate coexistence with IEEE 802.15 devices operating in unlicensed frequency bands, and suggests modifications to other IEEE 802.15 standards to enhance coexistence with other selected wireless devices operating in unlicensed frequency bands.
IEEE 802.15.4-2003 Initiation: 12/2002 Completion: 5/2003	This standard defines the protocol and interconnection of devices via radio communication in a personal area network (PAN). The standard uses carrier sense multiple access with a collision avoidance medium access mechanism and supports star as well as peer-to-peer topologies. It includes dynamic channel selection (DCS) and operates at low power, among other techniques, to support coexistence with other wireless devices.
802.11h-2003 Initiation: 12/2000 Completion: 9/2003	This amendment to IEEE std. 802.11-1999 provides mechanisms for dynamic frequency selection (DFS) and transmit power control (TPC) that may be used to satisfy regulatory requirements for operation in the 5 GHz band in Europe. However, it also is applied in other regulatory domains. This document has been superseded by IEEE std. 802.11-2007.
802.16a-2003 Initiation: 2/2002 Completion: 4/2003	This amendment to the 802.16-2001 standard expands its scope by extending the WirelessMAN air interface to address operational frequencies from 2–11 GHz. It also added DFS and TPC techniques (see 6.3.15 and 8.3.7.4, respectively). The standard includes an Annex (B.2) that discusses coexistence in license-exempt bands and provides interference analysis.
802.16.2-2004 Initiation: 9/2003 Completion: 3/2004	This revision of the 802.16.2-2001 added treatment of coexistence in the 2–11 GHz bands to the 802.16.2-2001 standard.

Table 1. *Comparison of various completed IEEE 802 standards projects relating to cognitive, dynamic spectrum access, and coexistence technologies.*

sents completed standards activities. All the completed standards to date deal with coexistence of one form or another. Coexistence standards that depend on manual coordination are included because they defined what constitutes interference and mechanisms to mitigate it. These laid the ground work for the automated detection and spectrum-sharing techniques that evolved later. Many of these standards include DFS and transmit power control (TPC) for the purpose of facilitating spectrum sharing. They are designed to detect the presence of other systems, dynamically modify their use of spectrum to protect primary users, and to allow sharing between systems using diverse protocol sets. They are almost identical in function to DSA systems and can be found within several IEEE 802 standards. More information can be found below.

The set of activities in Table 2 are ongoing activities being conducted under Standards Coordinating Committee (SCC) 41 (http://www.scc41.org/). This group is focused on DSA networks and has several standards currently in development. More can be found below. They are well known for their CR activities and have a broader scope than the previous coexistence-oriented activities that were or are being conducted in IEEE 802.

Table 3 addresses ongoing IEEE 802 activities related to CR technology. The first of these is 802.22 (http://grouper.ieee.org/groups/802/22/). The IEEE 802.22 working group is also well known for its cognitive radio activities. We provide greater details on this emerging standard. Finally, there are several other IEEE 802 activities that relate to cognitive standards but are less well known. We review some of these.

Completed Standards of Interest for CR

Although SCC 41 and IEEE 802.22 are the primary cognitive standards efforts today, many completed IEEE 802 standards already include CR/DSA-like capabilities or related building blocks. Most of these concepts have evolved from coexistence activities.

IEEE 802.15 was one of the first standards groups to grapple with coexistence issues. Many of the IEEE 802.15 protocols were required to share the same unlicensed band (2.4 GHz) used by IEEE 802.11. Systems implementing the 802.15 protocols generally are unable to communicate with systems implementing 802.11 protocols. Rather, they simply interfere with each other.

The IEEE 802.15.2 Task Group was developed to grapple with coexistence issues and did seminal work in defining what it meant to coexist, and how coexistence could be facilitated and measured. A recommended practice resulted from their work. IEEE 802.15.2 contains a collection of collaborative and non-collaborative techniques that can be applied to improve the coexistence between systems; particularly IEEE 802.11 and IEEE 802.15, but also in a more general sense. IEEE 802.15.2 defines coexistence as:

"*The ability of one system to perform a task in a given shared environment where other systems have*

Standard	Scope
IEEE P1900.1: Terminology and Concepts for Next Generation Radio Systems and Spectrum Management Initiation: 3/2005 Completion: Est. 12/2008	This standard will provide technically precise definitions and explanations of key concepts in the fields of spectrum management, cognitive radio, policy-defined radio, adaptive radio, software-defined radio, and related technologies. The document goes beyond simple, short definitions by providing amplifying text that explains these technologies. The document also describes how these technologies interrelate and create new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms such as dynamic spectrum access.
IEEE P1900.2: Recommended Practice for Interference and Coexistence Analysis Initiation: 3/2005 Completion: Est. 12/2008	This recommended practice will provide technical guidelines for analyzing the potential for coexistence or, in contrast, interference between radio systems operating in the same frequency band or between frequency bands.
IEEE P1900.3: Dependability and Evaluation of Regulatory Compliance for Radio Systems with Dynamic Spectrum Access Initiation: 5/2005 Completion: Est. 2/2011	This standard will specify techniques for testing and analysis to be used during compliance and evaluation of radio systems with dynamic spectrum access (DSA) capability. The standard also will specify radio system design features that simplify the evaluation challenge. Note that this is the updated scope and title as modified in 12/2007.
IEEE P1900.4: Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks Initiation: 12/2006 Completion: est. 12/2007	This standard will define the building blocks comprising 1) network resource managers, 2) device resource managers, and 3) the information to be exchanged between the building blocks, enabling coordinated network-device distributed decision-making which will aid in the optimization of radio resource usage, including spectrum access control, in heterogeneous wireless access networks. The standard will be limited to the architectural and functional definitions at the first stage. The corresponding protocol definitions related to information exchange will be addressed at a later stage.

Table 2. *Comparison of various ongoing IEEE SCC41 standards projects incorporating cognitive, dynamic spectrum access, and coexistence technologies.*

an ability to perform their tasks and may or may not be using the same set of rules."

Coexistence does not require the use of cognitive techniques. But cognitive techniques can be used to facilitate coexistence.

Another example of prior work in IEEE 802 groups relating to CR is the DFS and TPC capabilities added to IEEE 802.11 in IEEE 802.11h. These features deal with the fact that other systems (such as military radars) may operate in the unlicensed national information infrastructure (UNII) bands and require protection. The DFS features developed for 802.11 allow for the detection of military radar and the relocation of a potentially interfering 802.11 basic service set (BSS) to another frequency. The techniques developed for 802.11h can be applied to other bands and other systems with similar issues and can be leveraged by CR/DSA systems. IEEE 802.16-2004 is another standard that includes DFS and TPC capabilities. IEEE 802.15.4 includes dynamic channel selection (DCS), which is similar to DFS.

IEEE SCC41

The SCC41 sponsors standards projects in the area of dynamic spectrum access networks. The SCC41/P1900 activities are co-sponsored by the IEEE Communications and Electromagnetic Compatibility Societies. New techniques and methods of dynamic spectrum access require managing interference, coordination of wireless technologies, and include network management and information sharing. The SCC41 addresses standardization for these techniques.

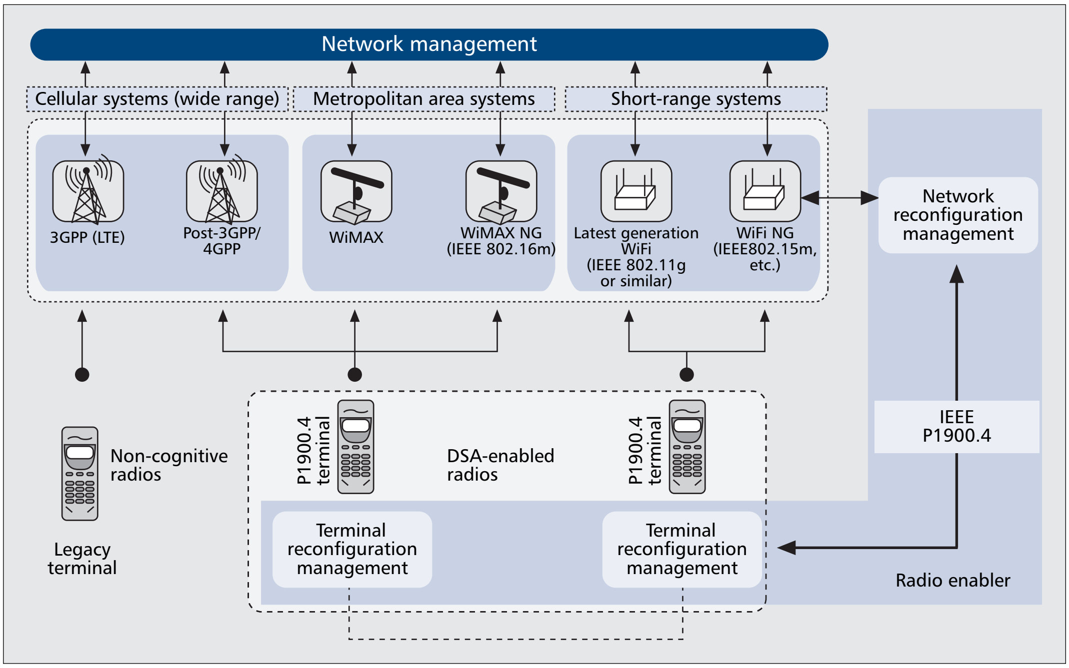
The SSC41 identifies its roots as originating with SDR technologies as a key enabler for CR/DSA [7]. It concentrates on developing architectural concepts and specifications for network management between incompatible wireless networks rather than specific mechanisms that can be added to the physical (PHY) or media access control (MAC) protocol layers. The IEEE SCC41 will provide vertical and horizontal network reconfiguration management methods for interoperability in infrastructure-less wireless networks. The SCC41 [8] is developing policy-based network management for dynamic spectrum access among third/fourth generation (3G/4G), WiFi, and worldwide interoperability for microwave access (WiMax) networks.

An example of the important work that is ongoing within the SCC41 is illustrated in Fig. 3 and shows the SCC41 concept of operations that enable spectrum management between cognitive and non-cognitive radio access networks (RANs). The network reconfiguration management (NRM) functions communicate with the terminal radio management (TRM) function to provide interoperability between the infrastructure-less wireless network environments. The dynamic spectrum access and management of these environments include distributed decision-making via policies for each network. Distributed decision-making for DSA management account for these capabilities. P1900.4-compliant infrastructure would allow for terminal and network reconfiguration to account for these factors and may be able to use the existing network infrastructure to enable seamless connectivity.

The individual working groups (WGs) of

Standard	Scope
IEEE 802.22 Initiation: 9/2004 Completion: Est. 9/2009	This standard specifies the air interface, including MAC and PHY layers, of fixed point-to-multipoint wireless regional area networks operating in the VHF/UHF TV broadcast bands between 54 MHz and 862 MHz. The unique requirements of operating on a strict non-interference basis in spectrum assigned to, but unused by, the incumbent licensed services requires a new approach using purpose-designed cognitive radio techniques that will permeate the PHY and MAC layers.
802.19 Initiation: 3/2006 Completion: Est. 9/2008	This recommended practice describes methods for assessing coexistence of wireless networks. The document defines recommended coexistence metrics and methods of computing these coexistence metrics. The focus of the document is on IEEE 802 wireless networks, though the methods developed may be applicable to other standards development organizations and development communities.
IEEE 802.16h Initiation: 12/2004 Completion: Est. 9/2008	This amendment to the 802.16 standard will specify improved mechanisms (as policies and medium access control enhancements) to enable coexistence among license-exempt systems based on IEEE standard 802.16 and to facilitate the coexistence of such systems with primary users.
IEEE 802.16m Initiation: 12/2006 Completion: Est. 12/2009	This amendment to the 802.16 standard will provide an advanced air interface for operation in licensed bands. It will meet the cellular layer requirements of IMT-advanced next-generation mobile networks while providing continuing support for legacy WirelessMAN-OFDMA equipment. It is possible cognitive technology may be introduced in this amendment.
IEEE 802.11y Initiation: 3/2006 Completion: Est. 12/2009	This amendment to the 802.11 standard will allow application of 802.11-based systems to the 3650–3700 MHz band in the U.S. It will standardize the mechanisms required to allow shared 802.11 operations with other users. Likely required mechanisms include: specification of new regulatory classes (extending 802.11j), sensing of other transmitters (extending 802.11a), transmit power control (extending 802.11h), dynamic frequency selection (extending 802.11h).

■ **Table 3.** *Comparison of various IEEE standards incorporating cognitive, dynamic spectrum access, and coexistence technologies.*

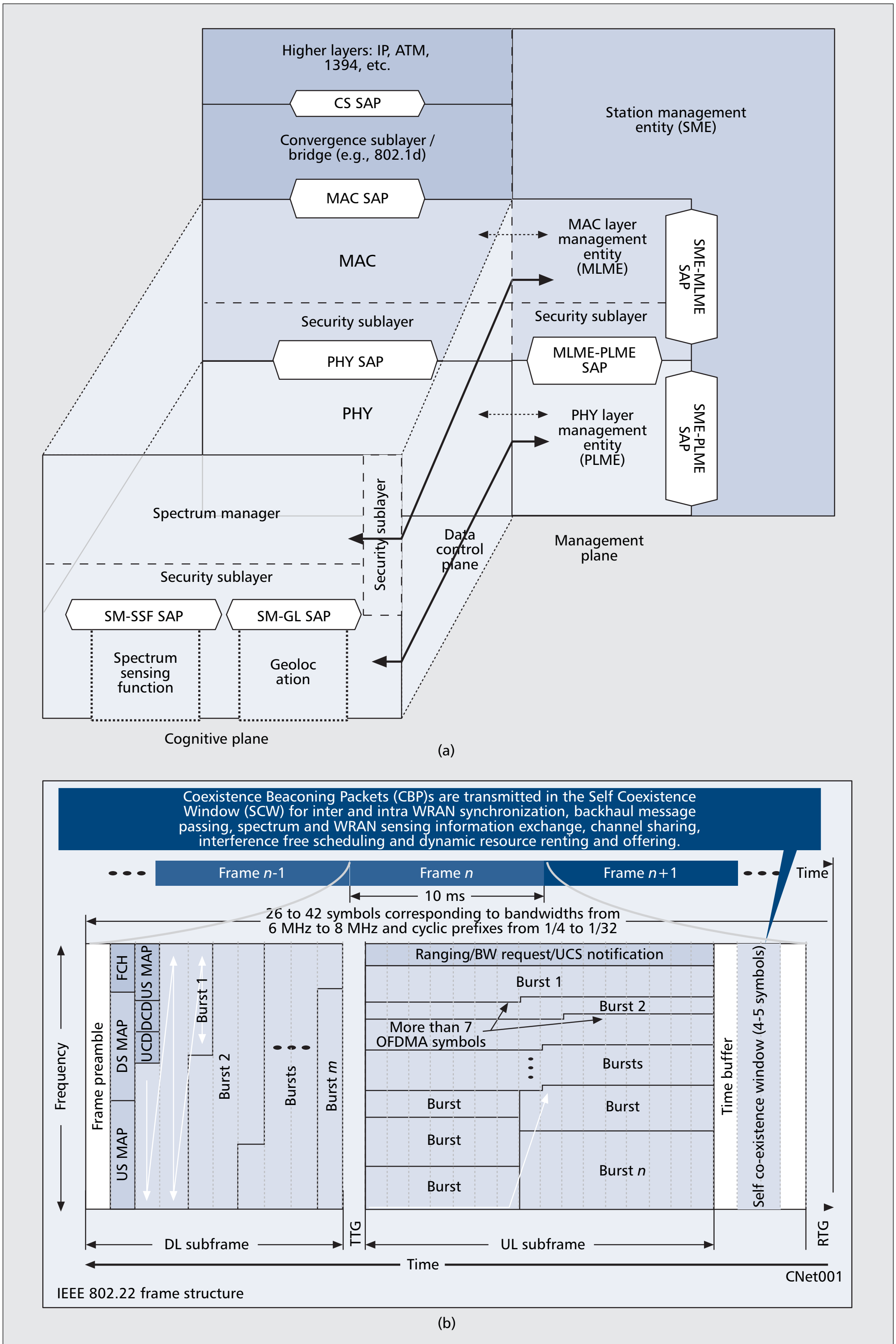


■ **Figure 3.** *The P1900.4 concept of operations (CONOPS) where terminals use CR techniques to operate across a variety of existing network infrastructures and maintain seamless connectivity.*

SCC41 are listed along with their scope and status in Table 2. It is anticipated that additional standardization activities will be conducted within the SCC41. The SCC41 recently proposed two new working groups to address policy language (P1900.5) and RF sensing (P1900.6). The goal of these groups is to develop the policy language framework using ontology-based languages and to address spectrum sensing functions that can be managed in the TRMs.

IEEE 802.22

In May 2004, in the landmark Notice of Proposed Rule Making (NPRM) 04-113 [3], the FCC announced the use of unlicensed wireless operation in the analog television (TV) bands. In response to this NPRM (and proceedings leading up to it), the IEEE 802 local area network/metropolitan area network (LAN/MAN) Standards committee created the 802.22 WG on wireless regional area networks (WRANs) with a CR-based air interface for



■ **Figure 4.** *a) A cognitive radio interface diagram for the IEEE 802.22 standard; b) the IEEE 802.22 frame structure, which is an extension of the IEEE 802.16e-2005 frame structure with the addition of a self-coexistence window (SCW).*

use by license-exempt devices on a non-interfering basis in VHF and UHF (54–862 MHz) bands. IEEE 802.22 will be the first complete cognitive radio-based international standard with frequency bands allocated for its use. Significant progress has been made toward the PHY, MAC, and cognitive domain definitions of the standard. A few essential features are highlighted below.

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IEEE 802.16 is intended for use in licensed and unlicensed bands. Coexistence issues have been a concern almost from the beginning. However, in 2004, project 802.16h was started to consider "improved coexistence mechanisms for license-exempt operation."

Figure 4a shows the proposed protocol referenced model (PRM) for a CR node that is likely to be adopted by the 802.22 WG. Definition of an appropriate PRM is important because it defines the system architecture, functionalities of various blocks, and their mutual interactions. The proposed PRM separates the system into the cognitive, data/control, and management planes. The data/control and management planes (non-cognitive components) look similar to other standards within the IEEE. The spectrum-sensing function (SSF) and geolocation function that interface with the RF stage of the device provide information to the spectrum manager (SM) on the presence of incumbent signals, as well as its current location. The SM function makes decisions on transmission of the information-bearing signals. The SM at the subscriber location is called the spectrum automaton (SA), because it is assumed that almost all of the intelligence and the decision-making capability will reside at the SM of the base station. The PHY, MAC, and convergence layers are essentially the same as in 802.16. Security sub-layers are added between service access points (SAPs) to provide enhanced protection.

Spectrum sensing was one of the major challenges for this standard until recently. TV broadcasters had set a stringent limit for the TV signals to be reliably detected (probability of detection > 90 percent with probability of false alarm < 10 percent) at a signal strength of –116 dBm translating to roughly –21 dB of signal-to-noise ratio (SNR) based on the receiver noise figure (NF) of around 11 dB and the use of omnidirectional antenna for spectrum sensing. However, there are currently at least three techniques that meet these stringent sensing requirements. One of these techniques was proposed by one of the authors of this article [9].

The FCC also mandates the protection of approved Part 74 devices such as the wireless microphones in these frequency bands. Because wireless microphones operate with lower bandwidth, lower power, and anywhere in a TV channel, they are difficult to detect and protect [10]. To facilitate their detection, a beacon signal will be constantly transmitted from specialized devices that will accompany the wireless microphone base stations. These beacon signals consist of repeated pseudo noise (PN) sequences and have a bandwidth of approximately 78 kHz with the center frequency at approximately the same location as that of the Advanced Television Systems Committee-Digital Television (ATSC-DTV) pilot signal of the channel currently occupied by the wireless microphone.

The 802.22 WG has adopted many of the PHY, MAC, security, and quality of service (QoS) features from the IEEE 802.16-2004 and 802.16e standards with some essential modifications due to the different propagation and operational scenario characteristics for WRANs. Because signals at VHF/UHF travel longer distances than those at higher frequencies, various WRAN cells using similar frequencies are likely to create co-channel interference. Hence, as compared to other standards, 802.22 has been quite proactive in addressing the issue of self-coexistence. Figure 4b shows the proposed IEEE 802.22 frame structure. The IEEE 802.22 frame structure is an extension of the IEEE 802.16-2004 and 802.16e frame structures except for an addition of a self coexistence window (SCW). Coexistence beaconing packets (CBPs) are transmitted in the SCW for inter-WRAN and intra-WRAN synchronization, backhaul message passing when backhaul connectivity is not available, spectrum- and WRAN-sensing information exchange, channel sharing, interference-free scheduling, dynamic resource renting and offering, and if all else fails, channel contention. The IEEE 802.22 draft standard document explains these functionalities in detail.

OTHER ONGOING WORK OF INTEREST FOR CR

IEEE 802.19 is a technical advisory group (TAG) within IEEE 802. IEEE 802.19 was created, based on the successes of 802.15.2, to act as a coexistence advisory committee across all of IEEE 802. It has spearheaded the creation of special rules focused on fostering coexistence within IEEE 802 standards operating in unlicensed bands. This includes monitoring the creation of coexistence assurance documents for new IEEE 802 wireless standards that could rely on cognitive techniques. Currently, 802.19 is working on a recommended practice for methods of assessing coexistence of wireless networks. When completed, these methods may be of use for cognitive systems.

IEEE 802.16 is intended for use in licensed and unlicensed bands. Coexistence issues have been a concern almost from the beginning. However, in 2004, project 802.16h was started to consider "improved coexistence mechanisms for license-exempt operation." The resulting standard likely will include cognitive capabilities and mechanisms that can be broadly applicable in many systems. As of this date, the current draft of this standard is "D3," and it is still being baloted within the 802.16 WG.

FUTURE DIRECTIONS FOR CR/DSA STANDARDIZATION

Although rudimentary cognitive capabilities (detection of other signals with application of dynamic frequency assignment, power control, and other techniques in response) already exist, many would say that existing standards have not yet risen to the point of being cognitive. But the promise and potential value of such techniques clearly is recognized, and almost all existing and future wireless standards are trying to incorporate cognitive radio, dynamic-spectrum access, and coexistence techniques.

In addition, as governments open and evaluate opening new bands specifically requiring the use of CR, these techniques are becoming increasingly sophisticated. There are many issues yet to be fully addressed such as recognizing and defining harmful interference, inter-modulation and out-of-band impacts, providing security within cognitive systems, and self- and inter-system coexistence. These issues must be sorted out before regulatory bodies such as the FCC will alter their policies and rulemaking. Even then, existing standardization efforts fall far short of the original CR vision put forward by Mitola nearly ten years ago.

What is lacking is the incorporation of other knowledge domains. Current cognitive radios account for knowledge of spectrum usage and to a limited degree, geolocation. This (spectrum utilization) is one knowledge domain. Other knowledge domains could include knowledge of the type of information to be accessed, knowledge of QoS and security requirements for data streams, and knowledge of available processing elements and databases in a network. CR capabilities also can exist outside the radio. It is believed that ultimately cognitive networking or cognitive communications will be more appropriate terms. Cognitive radio still is an active area of research, and as research progresses and comes into practice, further standardization work will be required to facilitate adoption of new techniques.

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CONCLUSIONS

Cognitive radio technology is advancing rapidly. Standardization is key to the current and future success of cognitive radio. This article has reviewed completed and on-going standards activities of interest for cognitive radio within IEEE. It also has considered future directions and standardization areas for cognitive radio technology.

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BIOGRAPHIES

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