INVITED PAPER

COGNITIVE RADIOS FOR DYNAMIC SPECTRUM ACCESS: FROM CONCEPT TO REALITY

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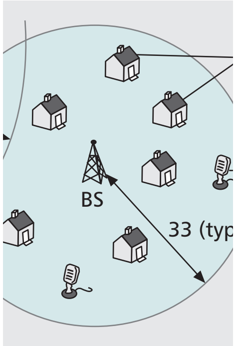

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ABSTRACT

This article provides a comprehensive survey of cognitive radio technology, focusing on its application to dynamic spectrum access, especially from the perspective of realizing consumer-oriented CR networks. We first overview the state of the art in CR technology and identify its key functions across the protocol stack, such as spectrum sensing, resource allocation, CR MAC protocol, spectrum-aware opportunistic routing, CR transport protocol, QoS awareness, spectrum trading, and security. We also review the various schemes proposed for each of these functions and discuss the suitability, advantages, and limitations of their usage in the future CR market. Finally, we introduce the activities in CR research communities and industry in terms of development of real-life applications, such as IEEE 802.22, Ecma 392, and IEEE 802.11af (also known as Wi-Fi 2.0 or White-Fi), and then identify necessary steps for future CR applications.

INTRODUCTION

Cognitive radio (CR) has opened up a new way of sensing and utilizing precious wireless spectrum resources. CR is a dynamically reconfigurable radio that can adapt its operating parameters to the surrounding environment, which has been made feasible by recent advances such as software-defined radio (SDR) and smart antennas. Using such CR devices enables flexible and agile access to the wireless spectrum, which can, in turn, improve efficiency in spectrum utilization significantly.

In particular, CR is considered key to resolving the soon-to-occur spectrum scarcity problem. Recent measurement studies have shown that the licensed spectrum bands are severely underutilized at any given time and location [1, 2], mainly due to the traditional *command-and-control* type spectrum regulation that has prevailed for decades. Under such a spectrum policy, each spectrum band is assigned to a designated party, which is given an exclusive spectrum usage right for a specific type of service and radio device.

CR can help mitigate the spectrum scarcity problem by enabling dynamic spectrum access (DSA), which allows unlicensed users/devices to identify the un-/underutilized portions of licensed spectrum and utilize them opportunistically as long as they do not cause any harmful interference to the legacy spectrum users' communications. The temporarily unused portions of spectrum are called spectrum white spaces (WS) that may exist in time, frequency, and space domains. In the context of DSA, the legacy users are called primary users (PUs) and the CR users are called secondary users (SUs). In addition, due to its dynamic nature, DSA is also referred to as *spectrum agility*.

We provide a comprehensive survey of CR technology focusing on its spectrum agility aspect. The application of CR to DSA has been actively studied over the past several years, covering diverse scenarios. However, the resultant research directions are fragmented, necessitating a more centralized view for the future of CR technology. In particular, we want to focus on the consumer-centric wireless network's perspective, since the success of CR technology hinges on its penetration in the commercial market.

The article is organized as follows. We provide a brief overview of the CR architecture and its functionalities. We provide a comprehensive survey of the current techniques for each CR function, and discuss their advantages and limitations in realizing consumer-based CR networks (CRNs). We introduce the real-life CR applications that have been developed or proposed thus far, and discuss open research issues in managing diverse CR applications that coexist in the legacy bands. Finally, the article concludes with possible future directions.

OVERVIEW OF CR'S STATE OF THE ART

The concept of CR was first proposed in 1999 by Joseph Mitola III in his pioneering work [3]. Since then, there has been rapidly increasing interest in CR due to its potential for reshaping the way of utilizing spectrum resources, leading

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to the FCC's initiation of a new spectrum policy in 2000 [4]. Through the continuing efforts of spectrum regulators (e.g., the FCC in the United States and the Office of Communications [Ofcom] in the United Kingdom) and the research community, CR will soon be applied to the TV white spaces (TVWS) through which it is expected to mitigate the anticipated spectrum shortage problem. In this section we briefly introduce the CR architecture, and provide an overview of the development of regulatory policies, industrial activities, and standardization.

ARCHITECTURAL OVERVIEW

The CR architecture can be viewed in the framework of the standard open systems interconnection (OSI) model, as illustrated in Fig. 1. In the physical (PHY) and link layers, *spectrum sensing* plays an essential role in discovering spectrum WS as well as protecting PUs, where PHY sensing employs various signal detection methods, such as energy and feature detection, and medium access control (MAC) sensing enhances the primary signal detection performance by:

- Employing multiple sensors (i.e., cooperative sensing), to exploit location diversity of sensors
- Directing them to perform sensing multiple times (i.e., sensing scheduling), to exploit temporal diversity in received primary signal strengths

Resource allocation and CR *MAC protocol* form other crucial parts of CR technology, and are designed to serve similar purposes as in traditional wireless networks. However, in a DSA network, they should be aware of and adapt to fluctuating spectrum availability, and be able to manage such time-varying spectrum resources efficiently. For example, dynamic channel selection and switching in CR devices require significantly tighter coupling between the PHY and link layers.

In the link and network layers, *spectrum-aware opportunistic routing* manages CR-based routing in a multihop environment via cross-layer interactions of link and network layers such that the best route can be determined by considering the hop-by-hop spectrum availability.

In the transport layer, the *CR transport protocol* is designed to enhance traditional transport protocols such as TCP/IP so that the impact of spectrum availability can be accounted for. This can be accomplished either by designing completely new transport protocols or through new management techniques of existing transport protocols.

In the application layer, *spectrum trading* is concerned with the transfer of dynamic spectrum usage right between PUs and SUs in terms of various market mechanisms including spectrum auction and leasing. Besides, a *geolocation* database provides easier means to check the presence of PUs in a spectrum band of interest by building a look-up table of PUs' channel usage patterns, especially when such patterns are highly predictable (e.g., TV users).

Finally, *quality of service (QoS) awareness* and *security* are also inherent CR functions that span over multiple layers, where the former provides solutions to spectrum-aware QoS provisioning, and the latter protects PUs and SUs from various threats that can disrupt efficient operation of core CR functions, such as spectrum sensing.

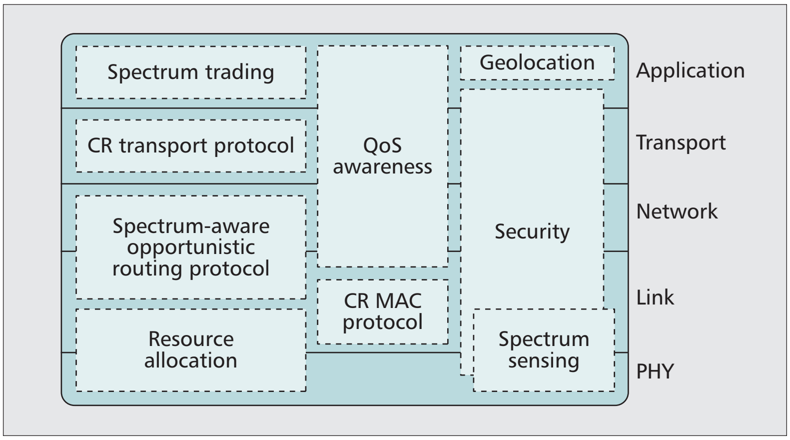

Figure 1. *The architecture of CR in the layered model.*

We discuss each of the above-mentioned CR technologies in detail later.

REGULATORY POLICY

In the United States the regulations on exploiting spectrum WS have been developed by the FCC. In 2000 the FCC released the first notice of proposed rulemaking (NPRM) [4], discussing the necessary actions to remove barriers to the development of the secondary spectrum markets. After proposing to allow unlicensed operation in TVWS [5], in 2008 the FCC specified the rules in such unlicensed transmission in rural and urban areas for fixed and personal/portable devices [6], thus paving the way for CR-based spectrum access.

In the United Kingdom Ofcom launched the Digital Dividend Review (DDR) project in 2005 to explore the options available after the analog to digital TV switchover. In [7] Ofcom proposed to allow license-exempt use of interleaved spectrum for cognitive devices and decided to allow cognitive access unless harmful interference is imposed on the licensed users. Recently, the Ofcom also proposed parameters for license-exempt CRs to provide PU protection [8], including those for spectrum sensing and geolocation databases.

There have also been worldwide efforts on spectrum deregulation. For example, the Korea Communications Commission (KCC) has adopted new spectrum policies for DSA and is considering opening up the TVWS [9]. According to the European Commission's (EC's) mandate, the Conference of European Post & Telecommunications Administrations (CEPT) has defined technical conditions and band plans for the use of the 790–862 MHz band by mobile/fixed communication networks (MFCNs) [10].

INDUSTRIAL ACTIVITIES

In 2008, to evaluate the potential of WS devices (WSDs), the FCC field tested prototype WSDs from Motorola, Philips, Adaptrum, and I2R in indoor and outdoor environments [11]. Each tested device was capable of performing a combination of functions including DTV sensing, wireless microphone (WM) sensing, transmis-

An alternative approach to spectrum sensing is to deploy beacon transmitters at PU locations, which periodically transmit "disabling beacons" with sufficiently strong power that any SU which detects the beacon may avoid using the channel.

sion, and geolocation, and the test results showed that the detection of TV signals in real environments is possible to some extent, while the detection of WMs is less reliable. As a result, the FCC recommended consulting both spectrum sensing and the geolocation database if available, to better protect the incumbents in the TV bands [6].

In 2009 the first public WS network was launched in Claudville, Virginia, using devices from Spectrum Bridge, Microsoft, and Dell [12], which later led to the first large-scale "Smart City" network in Wilmington, North Carolina, in 2010 [13]. Such movement has shown that TVWS has real market value and thus draws significant attention from the industry.

STANDARDIZATION

There have also been efforts to create international standards to utilize the TVWS using CR technology. One such example is the IEEE 802.22 wireless regional area network (WRAN) [14] designed for last-mile service in rural areas for fixed CR devices utilizing TVWS. For personal/portable devices, another standard has been developed, called Ecma 392 [15, 16], designed for services like in-home high-definition video streaming. In addition, IEEE 802.11af [17] tries to make a transition from traditional Wi-Fi to a Wi-Fi-like protocol operating over the TVWS. To cope with heterogeneous CR standards in the same band, other types of standards for coexistence are also considered, such as IEEE 802.19 and IEEE SCC 41 [15]. We discuss more ongoing standardization efforts later.

CONSUMER-ORIENTED CR TECHNOLOGIES

This section surveys the CR techniques developed thus far for each CR function introduced earlier, and discusses the prospects of their realization in consumer-oriented CRNs.

SPECTRUM OPPORTUNITY DISCOVERY

There have been a large number of proposals for discovery of spectrum WS, which can be categorized into three types based on:

- Detection of PU signals
- Detection of auxiliary beacons
- The use of a geolocation database of PUs

The PU signal detection is usually called spectrum sensing, and there are also MAC-layer supporting mechanisms to enhance the sensing performance, such as sensor collaboration and sensing scheduling. We first review each type of scheme and discuss their pros/cons in consumer-oriented CRNs.

Opportunity Discovery Schemes — Spectrum sensing employs digital signal processing techniques to identify PU signals in a licensed channel. PU signal detection is categorized as PU transmitter detection or PU receiver detection. The former includes energy and feature detection, where energy detection measures the energy level of the signal transmitted by a PU, whereas feature detection captures the specific signature of a PU signal, such as pilot, cyclostationarity [18], and covariances of signal and noise [19]. The latter has been considered for detection of passive PU receivers like TV receivers, where the leakage power from the local oscillator of a receiver [20] is captured by a leakage detector installed at each PU receiver.

An alternative approach to spectrum sensing is to deploy beacon transmitters at PU locations, which periodically transmit "disabling beacons" with sufficiently strong power that any SU which detects the beacon may avoid using the channel. This concept has been proposed by the IEEE 802.22 Working Group [14] to protect WMs in TV bands with small-scale footprints (up to 150 m) and is included in IEEE 802.22.1 [21].

In case the PUs' locations are known a priori, one can also use a geolocation database [22] that maintains location-specific maximum allowed transmit power levels that can be downloaded from the database server to each SU device. Thus, a GPS-equipped SU can look up the database to determine the availability of each channel.

Efficiency of opportunity discovery can also be enhanced by some prediction analysis on spectrum usage. For example, [23] introduced an extensive measurement study on spectrum usage in various locations and suggested the existence of significant correlation in spectrum usage patterns in terms of time, frequency, service, and space, which can be used to build an accurate prediction scheme on channel availability.

MAC-Layer Support — Due to the strict requirements of sensing performance (e.g., minimum sensitivity of –114 dBm in detecting DTV signals [14]), spectrum sensing requires MAC-layer support to enhance its single-time single-sensor performance, such as sensing scheduling [24, 25] and sensor collaboration [26–28]. Spectrum sensing is scheduled reactively or proactively to determine which channel to probe and how often. Collaborative sensing exploits the sensors' location diversity by assigning multiple sensors to sense a channel simultaneously in which the presence/absence of PUs is determined by combining multiple measurements via decision/data fusion [29].

However, various MAC-layer spectrum sensing overheads can adversely affect the throughput performance of SUs [28, 29]. Therefore, efficient spectrum sensing must be designed to minimize the sensing overhead while meeting the detectability requirements. For example, the fusion center must select a set of good sensors and schedule their sensing to maximally exploit spatio-temporal diversity in sensor readings. To achieve this goal, the performance gain and the MAC-layer sensing overhead must be considered together [28].

No Solution Fits All — As far as the TVWS are concerned, WSDs could operate with the geolocation database as a major control mechanism and use spectrum sensing as an extra measure of protection [6]. The disabling beacon mechanism is also used for detection of WMs, providing a beacon detection range of 7 km [21]. Although the aforementioned approach works well for fixed PUs, it may not work well for general CRNs operating in other legacy bands. For example, it may be infeasible to build a geolocation database for mobile PUs, since their locations constantly change. Besides, the disabling beacon method is not economically attractive since it requires change of all the PU transmitters deployed in the market, incurring excessive costs.

Therefore, direct detection of a primary signal is still necessary. The question is then which signal detection method to use. First, PU receiver detection may not be cost-efficient if the receivers are passive because it requires a leakage detector to be installed at every primary receiver. In terms of PU transmitter detection, energy and feature detection are the two most prominent methods. Energy detection is simple but susceptible to noise uncertainty, while feature detection is complex but more robust to noise uncertainty [30]. In [31] the authors compared energy and feature detection with respect to their sensing overhead, showing the existence of a signal-to-noise ratio (SNR) threshold below which feature detection outperforms energy detection in a shadow-fading environment.

In summary, the determination of the best opportunity discovery method highly depends on which licensed band is chosen by the CR applications. Nevertheless, spectrum sensing is still necessary for any type of CR operation; thus, more efficient and accurate PU signal detection schemes are needed to provide reliable and cheaper devices to CR customers.

CR MAC PROTOCOL

Link-level management of DSA is essential to improve spectrum usage efficiency via intelligent exploitation of the wireless medium, which is performed by a CR MAC protocol. The CR MAC protocol is the glue that binds disparate components to realize DSA, and manages various tasks such as data control, coordination of heterogeneous CR functions, and sensing scheduling. Structurally, the CR MAC protocol differs from the conventional MAC in that it is more tightly coupled with PHY and higher layers, as shown in Fig. 1.

Several CR MAC protocols have been proposed, such as C-MAC [32], OS-MAC [33], and WhiteFi [34], and standardization efforts for the CR MAC are also underway, including IEEE 802.22 [35] for WRANs and IEEE P1900 [36] for high-level DSA networks. In addition, the authors of [37] presented a general survey of CR-based MAC protocols proposed up to 2009.

Despite differences in low-level details, there are certain fundamental operations that must be present in every CR MAC protocol. From a functional perspective, there are three main components of a CR MAC protocol: *spectrum monitoring*, *decision making*, and *coordination*, as shown in Fig. 2.[1]

The spectrum monitoring (or spectrum sensing) component senses channels in the spectrum and acquires their characteristics. Its main goal is spectrum opportunity discovery, a crucial part of DSA, in a reliable and timely manner. The decision making component is primarily concerned with how best to exploit the observed (or predicted) spectrum opportunities. Thus, it determines the channel to use, supports resource allocation and management, and can also invoke "coordination" procedures, if needed, to coordinate its decisions across a CRN. Finally, the coordination component orchestrates the decision making in a multinode CRN, thus defining the network management mechanisms of a CR MAC protocol (e.g., how to exchange control notifications among nodes). In what follows, we elaborate on some of the important techniques used for these three CR MAC components.

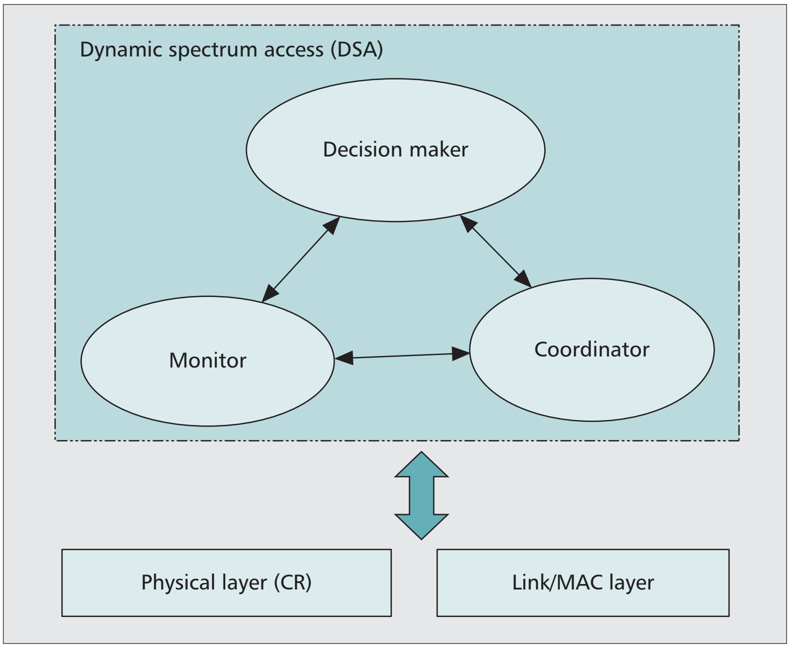

Figure 2. *Functional model of a typical DSA protocol.*

CR MAC protocols can be classified into several categories based on their approaches for the aforementioned key functional components. First, in terms of the network architecture, we can categorize them as *distributed* [32, 33, 38] or *centralized* [34, 35, 39]. In centralized CR MAC protocols (e.g., 802.22 [35]), the central controller node (e.g., the base station) is in charge of the management of the network, including CR operations. The controller node selects the data and control channels, typically based on the sensing reports from other nodes. It also controls other CR parameters for the network, such as data rates, transmit power, and cooperative spectrum sensing schedule. Typically, centralized CR MAC protocols feature regular beacon packets for network management and are suitable for infrastructure-based CRNs. In contrast, the decentralized CR MAC protocols (e.g., C-MAC [32]) are suitable for ad hoc networks. They typically feature negotiation-based network management based on conflict resolution metrics, such as first come first served (FCFS) or randomization.

Second, based on the techniques used for the coordination component, we can classify CR MAC protocols as *periodic-control-packets-based* [32], or *on-demand-control-packets-based* [33]. C-MAC [32] is an example of the first category, and has been designed as a decentralized architecture. Channel access is based on recurring superframes, including a slotted *beacon period* for exchanging information (e.g., sensing reports) when negotiating resource allocation. It utilizes

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[1] These functional elements are present in addition to the usual components in a typical MAC protocol, such as packet queue management and channel access mechanism.

a dynamically designated control channel, called the *rendezvous channel*, for coordination among nodes. In addition, C-MAC features incumbent coexistence and self-coexistence mechanisms. On the other hand, OS-MAC [33] is an example of the second category, which combines both licensed and unlicensed operations in its design for more efficient spectrum usage. Like C-MAC, it accommodates a decentralized architecture and uses a control channel for coordination. However, unlike C-MAC's recurring superframe structure, OS-MAC uses an on-demand channel access model with the listen-before-talk principle as in 802.11. Furthermore, it uses on-demand control packets rather than periodic beacons. Resource allocation (and load balancing) among nodes is done by delegate SUs' exchange of data traffic information on the control channel. Probabilistic channel switching is also proposed to avoid congestion on any particular channel.

As a unique feature among the CR MAC protocols proposed so far, HC-MAC [40] accounts for practical hardware constraints in its design.

The CR technology must ultimately be able to convert the resource gains at the spectrum/channel level into the performance gains for network applications. Application performance or its quality-of-service (QoS) improvement is critical because consumers directly interact with applications.

RESOURCE ALLOCATION AND MANAGEMENT

The discovered spectrum WS must be utilized intelligently to improve the spectrum efficiency and deliver a desired level of service quality to SUs. Here, we identify the key challenges in resource management in CRNs across the layers and review some of the existing work.

Power and Channel Allocation — Resource allocation in CRNs faces unique challenges due to the unpredictability of primary activity and the need for protecting primary communications. Unlike the traditional wireless systems, the availability of spectrum resources is time- and location-dependent based on PUs' characteristics such as their location and channel usage patterns. Thus, resource allocation in CRNs must be able to utilize dynamically changing spectrum resources efficiently and fairly to maximize spectrum utilization and/or secondary network throughput performance. Such CR-unique features — heterogeneous spectrum availability and the need for protecting primary communications — further complicate the resource allocation problem in CRNs.

To address such complex resource allocation in CRNs, graph-coloring-based heuristics for centralized/decentralized spectrum allocation was studied in [41]. In [42] the authors studied a local bargaining approach for distributed spectrum allocation, which dynamically adapts to the topological changes caused by user mobility, while providing a desired level of fairness. Resource allocation in multihop CRNs has also been considered in [43].

Resource allocation also needs to guarantee that SUs are not causing any harmful interference to PUs' communications. In CRNs each licensed channel may have different interference constraints, and hence a different power mask, depending on the PUs' activities on each channel. Therefore, channel and power allocation must be jointly considered to maximize secondary throughput performance while achieving fairness among SUs. The authors of [44] studied the problem of secondary spectrum access with the minimum SNR requirement for CR communications and interference temperature constraints. Recently, PU-SU cooperation has been considered in the design of joint channel and power allocation for both downlink and uplink communications in infrastructure-based CRNs [45]. In [46] the authors also discussed asymmetric resource allocation in a CRN when different interference patterns are generated by the use of heterogeneous — omnidirectional and directional — antennas.

Application-Centric Adaptation — CR technology must ultimately be able to convert the resource gains at the spectrum/channel level into performance gains for network applications. Application performance or its QoS improvement is critical because consumers directly interact with applications — it is the user-visible front-end of the underlying low-level networking protocols. Unless the consumer, through his/her networking experience, is convinced that there is substantial extra benefit from deploying CR technology, it can never be successful in the wireless market.

Although application performance/QoS is a crucial issue, it has often been neglected in the current generation of CR R&D efforts. It must be noted that DSA entails several fundamental operations, such as spectrum sensing and channel switching [38, 47], which may produce undesirable effects on applications. For example, there is a reduction in network bandwidth available to applications, and the end-to-end latency and jitter for network traffic can increase due to such disruptions. Besides, DSA semantics require that it must protect incumbent transmissions whenever they occur — which adds to the disruptions from DSA. Such unwarranted side-effects can have a substantial impact (e.g., retransmissions, connection re-establishments), depending on the specific spectrum region and DSA protocol used [48].

Thus, it is possible that DSA results in unstable behavior (under certain scenarios) from the end user's perspective. Thus, for DSA technology to become a reality in the mainstream, undesirable side-effects arising from lower-layer DSA operations must be effectively managed to mask their impact and reinforce the benefits of this technology at the application level.

In [49] the authors discussed the need for and importance of effective integration of higher-layer communication protocols with DSA schemes, particularly with routing and transport layers. They observed that the direct relationship of DSA functions to higher layers (including applications) necessitates a cross-layer design where spectrum management cooperates with the higher-layer entities. Application-centric cross-layer design has been found useful in diverse areas in networking, including power management [50], TCP congestion control [51], and mobile applications [52].

Cross-layer networking, however, is not without its own shortcomings, as noted in [53]. From a broader perspective, there is always tension between performance and modularity in computer system design [54]. Thus, the cross-layer architecture for DSA, though promising, must be properly designed in order to provide richer end-user experience. Recently, DSA researchers have started looking into such an approach. For instance, the authors of [55] proposed a cross-layer design to integrate TCP with DSA, which offers significant gains for network applications. A networking framework for directly relating applications to DSA, called Context-Aware Spectrum Agility (CASA), has been proposed in [56]. CASA features application-centric optimization of DSA operations. It manages fundamental DSA parameters like sensing frequency and channel switching dynamics, based on application traffic QoS requirements like bandwidth and delay.

CR NETWORK AND TRANSPORT PROTOCOL

As noted earlier, despite operating at the physical/link layers, CR directly affects the semantics and performance of most communication protocols at higher layers in the networking stack. There are two main reasons for this correlation. First, the operation of the higher-layer protocol depends directly on the channel state. Wireless routing protocols are key examples. Since the channel of operation (and its characteristics) can dynamically change when DSA is active, the wireless routing protocols (particularly in mesh and ad hoc networks) must be aware of such changes. Second, although CR technology achieves resource increase at the channel level, such gains may not be reflected in the performance of higher-layer protocols that are agnostic of CRs. In fact, it may even be detrimental to them due to its side-effects and disruptive operational environment. Transport protocols are typical examples of this category of protocols.

In short, the current suite of upper-layer communication protocols have been created based on existing networking paradigms. Thus, there is a need to account for CR-specific behavior in such protocols to ensure correctness and QoS awareness, as pointed out in [49]. We discuss some of the key research efforts toward this goal in the context of the two main elements of upper-layer networking: routing and transport protocols.

Spectrum-Aware Opportunistic Routing Protocols — For multihop wireless networks, new routing algorithms are necessary due to the dynamic nature of the physical layer (in both time and frequency domains) in CRs [49]. However, routing for DSA is still a less explored area. Proposed solutions so far, such as the one in [57], show that the cross-layer coupling of routing with the spectrum management of DSA is required. Furthermore, frequent rerouting should be expected in such networks due to fluctuations caused by unlicensed operation. Thus, it is critical that route selection and update mechanisms in the routing protocol have low overhead.

In contrast to the centralized approach to routing (as discussed in [57]), the authors of [58] proposed a decentralized routing scheme for CRNs. The routing method is based on conventional on-demand routing for ad hoc networks, but incorporates multiflow multifrequency scheduling for route selection to account for DSA semantics.

Multihop routing for CRNs is considered in [43, 59] as part of the optimal spectrum resource sharing problem, which is formulated as a mixed-integer nonlinear program. They include the multiple layer constraints and multiple paths for load balancing, which are important for routing in the presence of DSA.

In [60] a geographic-forwarding-based routing protocol called SEARCH is proposed for ad hoc networks. SEARCH is coupled with spectrum management, and features joint selection of path with channels. The routing metric incorporates incumbent activity to avoid poor channels. Furthermore, it uses Kalman filters to consider node mobility for selecting shorter paths.

Modeling and analysis of routing in CRNs is itself a challenging problem. An initial approach has been discussed in [61]. In this work the authors present an overlay graph model for describing the CRN, where each layer corresponds to a particular channel. Each physical node in the CRN is assigned as a subnode in each of the layers. Based on this layered topology model, channel assignment and route selection schemes were developed.

Transport Protocols — Transport protocols constitute the first true end-to-end layer in the networking stack. Thus, they directly define the application performance and the overall end-user experience. However, transport protocol research for CRNs is still in its infancy.

The few approaches proposed so far can be grouped into the two major categories below.

Building new transport protocols: Some have adopted the approach of designing the transport layer protocol from scratch for CRNs. The main advantage of this approach is the clean slate design, which promotes simplicity. For instance, the authors of [62] proposed a new transport protocol called TP-CRAHN for ad hoc CRNs. TP-CRAHN is aware of the underlying DSA activities at the link layer and handles end-to-end flow/congestion control based on the current state of DSA. TP-CRAHN borrows its design extensively from TCP (e.g., for connection establishment and termination). In [63] a unified adaptive transport layer (ATL) suite is proposed in order to adapt to the heterogeneity of wireless networks expected in fourth-generation (4G) systems. Although the work is mainly focused on ensuring effective transport layer performance across heterogeneous wireless architectures/systems, it can be leveraged for DSA-based WLANs as well.

Management of existing transport protocols: There are two main disadvantages associated with the approach of building new DSA-aware transport protocols. First, they require the overall networking infrastructure (including end devices) to make necessary changes to support the new protocol. More important, they may not be compatible with existing transport protocols, which can prevent non-disruptive integration of CRNs with the existing networks (e.g., the Internet). To address these concerns, the authors of [55] proposed a TCP connection management framework for infrastructure (single-hop) CRNs, called DSASync, that works with no modifications or reloading of existing transport protocols. DSASync comprises algorithms based on buffer-

The current suite of upper-layer communication protocols have been created based on existing networking paradigms. Thus, there is a need to account for CR-specific behavior in such protocols to ensure correctness and QoS-awareness.

Despite the recent advances at the network and transport layers, there is still some distance to go before CR technology can be effectively assimilated. For instance, the CR routing protocols proposed thus far are not effective at low overhead and scalable route selection/coordination in decentralized networks.

ing and traffic-shaping to manage both inbound and outbound TCP traffic from a CRN.

Effective Solution is Still Elusive — Despite the recent advances at the network and transport layers, there is still some distance to go before CR technology can be effectively assimilated. For instance, the CR routing protocols proposed thus far are not effective at low-overhead and scalable route selection/coordination in decentralized networks. A major problem is to communicate frequent route failures and subsequent route updates arising due to frequent CR-related activities. The approach of using a control channel for routing updates has been explored, but it requires extra resources (e.g., a dedicated control interface). Furthermore, the control channel can be overloaded and present a communication bottleneck.

Similarly, almost all the work in the CR transport layer area has been related to connection-oriented protocols (e.g., TCP). Connectionless transport protocols (e.g., UDP), which carry a sizable fraction of network traffic today, have still not been considered in literature.

SPECTRUM TRADING

The advent of DSA has introduced new spectrum sharing models between PUs and SUs. According to [47], the current spectrum management is categorized as *command-and-control*, where the regulatory bodies, such as the FCC and Ofcom, explicitly set the spectrum usage rules and determine the type of services to be used.

DSA can alter the current static regulation to be more flexible, such as *exclusive-use*, *shared-use*, and *commons* [47]. In the exclusive-use model, licensees can dynamically transfer their spectrum usage rights to SUs in the framework of the dynamic spectrum market (DSM) or the secondary market using periodic spectrum auction. However, the services used for opportunistic access should still be the same as the licensees, which limits the model's applicability. There have been numerous attempts to derive truthful and collusion-resistant dynamic auction mechanisms [64–66].

In the shared-use model, SUs are allowed to access licensed spectrum more dynamically without any explicit approval from the licensees. The shared-use model is further categorized into either interleave or underlay, where the former discovers and utilizes the spectrum WS (e.g., with the help of spectrum sensing), and the latter implements a concurrent but indestructive type of spectrum sharing such as ultra-wideband (UWB) systems. For example, such schemes assuming spectrum sensing [24, 25, 67] fall into the shared-use model.

Finally, the commons model is the most advanced version of DSA where three types of variation are possible: *uncontrolled commons*, *managed commons*, and *private commons*. Uncontrolled commons implies unlicensed spectrum access with minimal regulations as found in the industrial, scientific, and medical (ISM) and unlicensed national information infrastructure (U-NII) bands, and managed commons implies unlicensed access under the control of regulatory parties as found in the government-controlled 3650 MHz band. Private commons was introduced in [68], which promotes gradual integration of opportunistic access devices in the licensed bands by allowing the PUs to supervise such access and possibly charge the SUs for sharing their spectrum. One such example is found in [69] where SUs are allowed to access unoccupied portions of licensed bands for which they are charged according to the tariff set by the licensees.

Toward More Market-Friendly Spectrum Sharing — DSA is of high economic value since not only can it enhance spectrum utilization, but it could also introduce new customer-oriented wireless services that can provide license holders with extra profit via spectrum leasing. Therefore, we evaluate spectrum sharing models in the context of promoting customer-friendly CR markets.

The shared-use model requires tight regulation by the FCC while incurring no monetary benefit for the PUs. In contrast, the exclusive-use model is an attractive choice for the license holders as they can lease their channels to SUs to make extra profit without introducing any harmful interference to PUs. However, a dynamic spectrum transfer cannot be done in real time, and SUs are restricted to use the same type of service as the PUs (i.e., they cannot introduce new CR services).

On the other hand, the commons model suggests an excellent way of sharing spectrum by providing benefits to both PUs and SUs. Of the three variations, uncontrolled and managed commons are limited to a specific band (e.g., ISM, U-NII, and 3650 MHz), and thus are not generally applicable to the already licensed bands. By contrast, the private commons model is considered a viable option in the long run [47] due to the increased revenue for the licensees.

In terms of spectrum trading, there could be several variations. Spectrum auction is arguably the most actively studied, which introduces new challenges, such as the competition between CR wireless service providers (WSPs) in leasing the limited amount of spectrum available in the DSM [70]. Another possible type of spectrum trading is spectrum renting, where each licensee can make an independent decision on leasing his/her own spectrum to a specific group of SUs [71].

SECURE CR COMMUNICATIONS

Success of DSA depends critically on secure operations of core CR functions. However, making them secure is challenging since CRNs are vulnerable to various attacks due to CR's unique features, such as easy access to the low-layer stacks in SDRs, and the lack of coordination between primary and secondary systems. In particular, significant benefits of DSA can only be achieved when SUs can reliably detect available spectrum WS, and all the SUs abide by the spectrum etiquette in using the thus discovered spectrum WS. Here, we discuss the research efforts to achieve the above two key functions: *secure* spectrum sensing and enforcing *spectrum etiquette* on CR users.

Secure Spectrum Sensing — There are two types of attack that exploit the vulnerabilities in spectrum sensing, primary user emulation attack (PUEA) and spectrum sensing data falsification (SSDF).

Defense against PUEA — The main objective of PUEA is to force SUs to vacate or stay away from a licensed channel by transmitting a fake primary signal when SUs sense the channel. A straightforward way of identifying such fake primary signals is to estimate the location of the signal source and compare it with the true location of the primary transmitter, as proposed in [72]. Another approach is to exploit the PHY-layer signal characteristics to verify the authenticity of a primary signal. For example, the authors of [73] proposed to jointly exploit the location-dependent link signature (i.e., multipath fading profile) and conventional cryptographic authentication. In a similar context, the authors of [74] proposed to inject a watermark signal into each incumbent transmission for authentication.

Defense against SSDF — Ensuring the robustness of cooperative sensing is of critical importance to the realization of DSA. However, it is challenging to achieve this goal since the strict detectability requirement imposed by the regulatory body (e.g., the FCC) renders the performance of cooperative sensing highly sensitive to manipulated (or erroneous) sensor reports [75, 76]. The impact of such sensing report manipulation attacks on detection performance can be mitigated by employing reputation-based decision/data fusion schemes. For example, [77] proposed to assign different weights to sensor reports according to sensors' reputation based on their history of reports. An alternative approach is to filter out abnormal sensing reports before the fusion center (or the base station [BS]) makes a final decision. A simple statistics-based filtering method was proposed in [75], where the BS prefilters outliers based on the mean and variance of sensing reports. Signal propagation characteristics in the PHY layer has also been exploited in [76] where the BS detects abnormal sensing reports by cross-validating the shadow-fading-induced correlation in sensing reports among neighboring sensors.

Enforcing Spectrum Etiquette — Spectrum WS can be utilized most efficiently and fairly when all the CRs abide by a common spectrum etiquette. However, the open architecture of low-layer stacks in SDR devices (e.g., USRP [78]) allows CRs to easily break the rules and behave selfishly. Such misuse of spectrum WS can be a major obstacle to the success of DSA, so detecting/punishing such misbehavior is of critical importance. One approach to prevent CR devices violating spectrum etiquettes is to implement monitoring/punishing mechanisms in hardware [79]. The unauthorized use of licensed spectrum can also be detected by external monitoring devices by exploiting the predictability of wireless signal propagation characteristics such as path loss [80]. The incentive mechanism for enforcing/enticing SUs to observe spectrum etiquette has also been studied in [81].

Potential Security Threats — While most existing work focused on accurate detection of the presence/absence of legitimate primary signals, attackers may distort some information regarding other fundamental PU characteristics, such as their location and transmit power level. Without ensuring the correctness of such PU characteristics, it is difficult to achieve efficient spectrum utilization with sufficient primary protection. Moreover, the design of defense mechanisms against attacks on higher-layer protocols as well as cross-layer protocols is still an open problem that requires further investigation.

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CR STANDARDS AND APPLICATIONS

In [6] the FCC allowed the introduction of two types of unlicensed devices in the TVWS, including fixed devices with up to 4 W of transmission power and personal/portable devices with up to 100 mW of power. Responding to the recommendation, there have been two emerging international standards: IEEE 802.22 and Ecma 392. IEEE 802.22 is designed for last-mile service in rural areas with fixed devices including the BS and the end-customer devices called customer premises equipment (CPE). Ecma 392 has been proposed more recently to create an international standard for the personal/portable use of TVWS in urban areas. IEEE 802.11af (also known as Wi-Fi 2.0 or White-Fi) has also been introduced as a potential application of CR that may enhance the capacity and services of current Wi-Fi systems by utilizing the TVWS, which provides better channel propagation characteristics.

In this section we introduce each CR application and discuss its prospects for realizing the consumer-oriented CR market.

IEEE 802.22

The IEEE 802.22 WRAN is an infrastructured cellular network where the BS covers an area of radius spanning from 30 km (typical) to 100 km. The WRAN end user is referred to as CPE whose transceivers are installed on a house. A conceptual illustration of IEEE 802.22 is provided in Fig. 3.

The WRAN is designed to provide throughput of 1.5 Mb/s in the downstream and 384 kb/s in the upstream, and its PHY utilizes OFDM modulation to overcome possibly excessive delays in a wide coverage area [82]. In addition, it provides PU protection such as spectrum sensing and a geolocation database for PU-SU coexistence, and also supports self-coexistence between WRANs via the Coexistence Beacon Protocol (CBP).

IEEE 802.22 is the first international CR standard, so it can become a touchstone for the potential of CR technology. However, we believe that alongside the technical completeness of the draft standard, it is also necessary to provide assurance to the market that the WRAN could create a profitable service in rural areas by considering the following two major investment costs: deployment cost of WRAN infrastructure (e.g., BSs, good [thus expensive] sensors, and geolocation databases), and the cost of manufacturing CPEs equipped with sophisticated sensors and optional directional antennas.

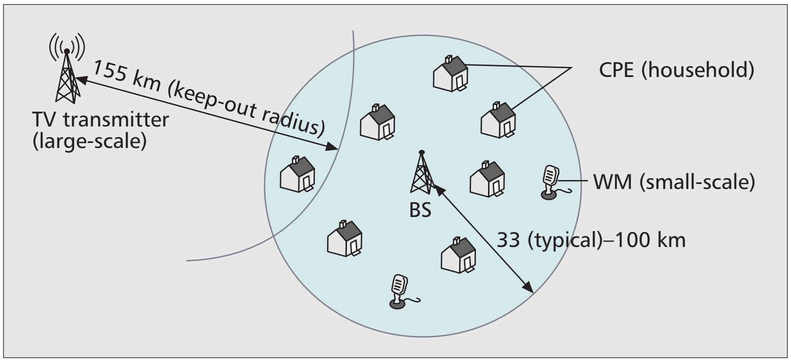

Figure 3. *An illustration of the IEEE 802.22 network.*

ECMA 392

Ecma 392 is the first CR standard for personal/portable devices to exploit the TVWS [15]. It was started by the Cognitive Networking Alliance (CogNeA), and a draft specification was later transferred to TC48-TG1. The standard specifies PHY and MAC layers with several characteristics: flexible network formation, adaptation to different regulatory requirements, and support for real-time multimedia traffic [15]. Ecma 392 is expected to enable new applications using TVWS such as in-home HD video transmission, campus-wide wireless coverage, and interactive TV broadcasting services.

Ecma 392 has potential to deliver high-quality WS services in developed areas. However, such populated regions will introduce a more challenging environment for PU protection due to the high volume of DTV receivers and WMs. Therefore, it is important to determine safe operational conditions according to various service scenarios. TVWS may also create an interference-prone environment between neighboring CRNs due to the characteristics of TV bands offering wider coverage, unlike the 60 GHz band in-home networks targeting short-range communications. As a result, a comparison study is necessary to explore the benefits of personal WS applications against other technologies, such as 802.11n or 60 GHz, that do not rely on the WS.

IEEE 802.11AF

The FCC's allowance of personal/portable devices [6] in TVWS introduces another interesting application: IEEE 802.11af [17]. In 2008 Google and Microsoft announced their interest in using TVWS for an enhanced type of Wi-Fi like Internet access, called *Wi-Fi 2.0*, *Wi-Fi on-steroids*, or *White-Fi* [83, 84]. The idea was later formalized as a new standard called *IEEE 802.11af*, for which an 802.11 task group was chartered. 802.11af is expected to provide much higher speed and wider coverage than current Wi-Fi, thanks to the better propagation characteristics of the VHF/UHF bands.

IEEE 802.11af can be modeled as a wireless network with a CR-enabled access point (AP) and associated CR devices as end terminals. The CR APs operate on spectrum WS via spectrum trading schemes, and the thus incurred time-varying spectrum availability introduces new challenges. For example, upon appearance of PUs in a leased channel, the AP should relocate the CRs in the channel, which requires eviction control of in-service customers [69] in case the remaining idle channels cannot accommodate all the spectrum demands.

Although Wi-Fi over WS is still in its infancy, its resemblance to today's Wi-Fi hotspots suggests that it may become a "killer application" in CR-based wireless networks. By utilizing more favorable spectrum bands than the ISM, the new Wi-Fi must be able to support QoS guarantees and resource-intensive multimedia services more easily than the current Wi-Fi.

OTHER EMERGING CR STANDARDS

The creation of various CR standards will lead to coexistence problems between dissimilar CR applications. In addition, the legacy services may want to actively coexist with SUs by providing some means of cooperation. Here, we categorize them into *SU-SU coexistence* and *PU-SU cooperation*, discussed next.

The advent of new CR standards will introduce new types of interference between collocated heterogeneous CRNs. To cope with such a situation, there are two standards under development: IEEE 802.19 and IEEE SCC 41 [15]. IEEE 802.19 deals with coexistence between unlicensed wireless networks, such as 802.11, 802.15, 802.16, and 802.22. On the other hand, IEEE SCC 41, previously known as IEEE 1900, defines higher-layer standards for DSA networks in the layers higher than MAC and PHY.

To aid development of the secondary wireless markets, the legacy network operators may provide some fraction of their spectrum on a payment basis for DSA. In such a case, the legacy network may want to provide a method of cooperation with the secondary network to ease the SUs' burden for PU protection (e.g., spectrum sensing). For example, the legacy network protocol provides explicit *PU-free periods* during which the SUs can access the licensee's channel.

CONCLUSION

In this article we have overviewed CR technology from the perspective of realizing the future consumer-centric CR market. The various schemes proposed thus far have been reviewed and compared to identify which of them to use for real-life CR applications. We have also introduced the CR standards and protocols currently under development including IEEE 802.22, Ecma 392, and IEEE 802.11af.

We believe that the current CR research directions should be steered toward consumer-oriented scenarios so as to enable seamless adaptation of DSA to legacy networks. Among others, possible future directions may include opportunity-discovery mechanisms minimizing network overhead (e.g., coordination between spectrum sensors) to promote flexible network topologies with less control, spectrum-aware network architectures designed to accommodate popular customer applications such as video streaming, and spectrum-trading mechanisms to enable elastic spectrum reuse for various CR applications.

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REFERENCES

[1] M. McHenry, "NSF Spectrum Occupancy Measurements Project Summary," Shared Spectrum Company Report, Aug. 2005; http://www.sharedspectrum.com/measurements.

[2] M. McHenry *et al.*, "Chicago Spectrum Occupancy Measurements & Analysis and A Long-Term Studies Proposal," *Proc. ACM TAPAS*, Aug. 2006.

[3] J. Mitola and G. Q. Maguire, "Cognitive Radio: Making Software Radios More Personal," *IEEE Pers. Commun.*, vol. 6, no. 4, Aug. 1999, pp. 13–18.

[4] FCC, "Notice of Proposed Rulemaking," ET Docket No. 00-402, Nov. 2000.

[5] FCC, "Notice of Proposed Rulemaking," ET Docket No. 04-113, May 2004.

[6] FCC, "Second Report and Order And Memorandum Opinion and Order," ET Docket No. 08-260, Nov. 2008.

[7] Ofcom, "A Statement On Our Approach To Awarding the Digital Dividend," *Digital Dividend Review*, Dec. 2007.

[8] Ofcom, "Digital Dividend: Cognitive Access," *Digital Dividend Review*, Feb. 2009.

[9] C.-J. Kim *et al.*, "Dynamic Spectrum Access/ Cognitive Radio Activities in Korea," *Proc. IEEE DySPAN*, Apr. 2010.

[10] H. R. Karimi *et al.*, "European Harmonized Technical Conditions and Band Plans for Broadband Wireless Access in the 790-862 MHz Digital Dividend Spectrum," *Proc. IEEE DySPAN*, Apr. 2010.

[11] OET, "Evaluation of the Performance of Prototype TV-Band White Space Devices Phase II," OET rep. FCC/OET 08-TR-1005, Oct. 2008.

[12] Spectrum Bridge, "The Nation's First White Spaces Network: Press Release," Oct. 2009; http://spectrumbridge.com/web/images/pdfs/PR/claudvillewhitespace-project-pressrelease.pdf.

[13] —, "TV white Spaces Powering Smart City Services," 2010; http://spectrumbridge.com/web/images/pdfs/smartcityspectrumbridge.pdf.

[14] IEEE 802.22 Working Group on Wireless Regional Area Networks; http://www.ieee802.org/22/.

[15] J. Wang *et al.*, "First Cognitive Radio Networking Standard for Personal/Portable Devices in TV White Spaces," *Proc. IEEE DySPAN*, Apr. 2010.

[16] "Standard ECMA-392: MAC and PHY for Operation in TV White Space," Dec. 2009; http://www.ecmainternational.org/publications/standards/Ecma-392.htm.

[17] R. Kennedy and P. Ecclesine, "IEEE P802.11af Tutorial," IEEE 802.11-10/0742r0, July 2010; https://mentor.ieee.org/802.11/dcn/10/11- 10-0742-00-0000-p802-11af-tutorial.ppt.

[18] A. Fehske, J. Gaeddert, and J. H. Reed, "A New Approach to Signal Classification Using Spectral Correlation and Neural Networks," *Proc. IEEE DySPAN*, Nov. 2005.

[19] Y. Zeng and Y.-C. Liang, "Covariance Based Signal Detections for Cognitive Radio," *Proc. IEEE DySPAN*, Apr. 2007.

[20] B. Wild and K. Ramchandran, "Detecting Primary Receivers for Cognitive Radio Applications," *Proc. IEEE DySPAN*, Nov. 2005.

[21] G. J. Buchwald *et al.*, "The Design and Operation of the IEEE 802.22.1 Disabling Beacon for the Protection of TV Whitespace Incumbents," *Proc. IEEE DySPAN*, Oct. 2008.

[22] D. Gurney *et al.*, "Geo-Location Database Techniques For Incumbent Protection in the TV White Space," *Proc. IEEE DySPAN*, Oct. 2008.

[23] D. Chen *et al.*, "Mining Spectrum Usage Data: A Large-Scale Spectrum Measurement Study," *Proc. ACM MobiCom*, Sept. 2009.

[24] H. Kim and K. G. Shin, "Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks," *IEEE Trans. Mobile Comp.*, vol. 7, no. 5, May 2008, pp. 533–45.

[25] N. B. Chang and M. Liu, "Optimal Channel Probing and Transmission Scheduling for Opportunistic Spectrum Access," *Proc. ACM MobiCom*, Sept. 2007.

[26] A. Ghasemi and E. S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *Proc. IEEE DySPAN*, Nov. 2005.

[27] G. Ganesan and Y. Li, "Cooperative Spectrum Sensing in Cognitive Radio, Part II: Multiuser Networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, June 2007, pp. 2214–22.

[28] A. W. Min and K. G. Shin, "An Optimal Sensing Framework based on Spatial RSS-Profile in Cognitive Radio Networks," *Proc. IEEE SECON*, June 2009.

[29] Y.-C. Liang *et al.*, "Sensing-Throughput Tradeoff for Cognitive Radio Networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, Apr. 2008, pp. 1326–37.

[30] R. Tandra and A. Sahai, "SNR Walls for Signal Detection," *IEEE J. Sel. Topics Signal Proc.*, vol. 2, no. 1, Feb 2008, pp. 4–16.

[31] H. Kim and K. G. Shin, "In-Band Spectrum Sensing in Cognitive Radio Networks: Energy Detection or Feature Detection?," *Proc. ACM MobiCom*, Sept. 2008.

[32] C. Cordeiro and K. Challapali, "C-MAC: A Cognitive MAC Protocol for Multi-Channel Wireless Network," *Proc. IEEE DySPAN*, Apr. 2007.

[33] B. Hamdaoui and K. G. Shin, "OS-MAC: An Efficient MAC Protocol for Spectrum-Agile Wireless Networks," *IEEE Trans. Mobile Comp.*, vol. 7, no. 7, July 2008.

[34] P. Bahl *et al.*, "White Space Networking with Wi-Fi Like Connectivity," *Proc. ACM SIGCOMM*, Aug. 2009.

[35] C. Cordeiro, K. Challapali, and D. Birru, "IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios," *J. Commun.*, vol. 1, no. 1, Apr. 2006, pp. 38–47.

[36] IEEE Standards Coordinating Committee 41 (Dynamic Spectrum Access Networks), http://www.scc41.org.

[37] C. Cormio and K. R. Chowdhury, "A Survey on MAC Protocols for Cognitive Radio Networks," *Ad Hoc Net. (Elsevier)*, vol. 7, no. 7, Sept. 2009.

[38] C.-T. Chou *et al.*, "What and How Much to Gain by Spectral Agility?," *IEEE JSAC*, vol. 25, no. 3, Apr. 2007.

[39] S. Y. Lien, C. C. Tseng, and K. C. Chen, "Carrier Sensing Based Multiple Access Protocols for Cognitive Radio Networks," *Proc. IEEE ICC*, May 2008.

[40] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management," *IEEE JSAC*, vol. 26, no. 1, Jan. 2008.

[41] C. Peng, H. Zheng, and B. Y. Zhao, "Utilization and Fairness in Spectrum Assignment for Opportunistic Spectrum Access," *ACM/Springer Mobile Networks and Application*, vol. 11, no. 4, Aug. 2006.

[42] L. Cao and H. Zheng, "Distributed Spectrum Allocation Via Local Bargaining," *Proc. IEEE SECON*, Sept. 2005.

[43] Y. T. Hou, Y. Shi, and H. D. Sherali, "Optimal Spectrum Sharing for Multi-Hop Software Defined Radio Networks," *Proc. IEEE INFOCOM*, May 2007.

[44] Y. Xing *et al.*, "Dynamic Spectrum Access with QoS and Interference Temperature Constraints," *IEEE Trans. Mobile Comp.*, vol. 6, no. 4, Apr. 2007, pp. 423–33.

[45] A. T. Hoang, Y.-C. Liang, and M. H. Islam, "Power Control and Channel Allocation in Cognitive Radio Networks with Primary Users' Cooperation," *IEEE Trans. Mobile Comp.*, vol. 9, no. 3, Mar. 2010, pp. 348–60.

[46] H. Kim and K. G. Shin, "Asymmetry-Aware Real-Time Distributed Joint Resource Allocation in IEEE 802.22 WRANs," *Proc. IEEE INFOCOM*, Mar. 2010.

[47] M. M. Buddhikot, "Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges," *Proc. IEEE DySPAN*, Apr. 2007.

[48] A. Kumar *et al.*, "A Case Study of QoS Provisioning in TV-Band Cognitive Radio Networks," *Proc. IEEE ICCCN*, Aug. 2009.

[49] I. F. Akyildiz *et al.*, "Next Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey," *Comp. Net. J.*, vol. 50, no. 13, Sept. 2006, pp. 2127–59.

[50] M. Anand, E. B. Nightingale, and J. Flinn, "Ghosts in the Machine: Interfaces for Better Power Management," *Proc. ACM MobiSys*, 2004.

[51] X. Yu, "Improving TCP Performance 0ver Mobile Ad Hoc Networks by Exploiting Cross-Layer Information Awareness," *Proc. ACM MobiCom*, Sept. 2004.

[52] M. J. Sinderen *et al.*, "Supporting Context-Aware Mobile Applications: An Infrastructure Approach," *IEEE Commun. Mag.*, vol. 44, no. 9, Sept. 2006, pp. 96–104.

[53] S. Shakkottai, T. S. Rappaport, and P. C. Karlsson, "Cross-Layer Design for Wireless Networks," *IEEE Commun. Mag.*, vol. 41, no. 10, Oct. 2003, pp. 74–80.

[54] B. Lampson, "Hints for Computer System Design," *Proc. ACM SOSP*, 1983, pp. 33–48.

To aid development of the secondary wireless markets, the legacy network operators may provide some fraction of their spectrum on a payment basis for DSA. In such a case, the legacy network may want to provide a method of cooperation with the secondary network to ease the SUs' burden for PU protection.

[55] A. Kumar and K. G. Shin, "Managing TCP Connections in Dynamic Spectrum Access Based Wireless LANs," *Proc. IEEE SECON*, June 2010.

[56] A. Kumar and K. G. Shin, "Extended Abstract: Towards Context-Aware Wireless Spectrum Agility," *Proc. ACM MobiCom*, Sept. 2007.

[57] Q. Wang and H. Zheng, "Route and Spectrum Selection in Dynamic Spectrum Networks," *Proc. IEEE CCNC*, Jan. 2006.

[58] G. Cheng *et al.*, "Spectrum Aware On-Demand Routing in Cognitive Radio Networks," *Proc. IEEE DySPAN*, Apr. 2007.

[59] Y. T. Hou, Y. Shi, and H. D. Sherali, "Spectrum Sharing for Multi-Hop Networking with Cognitive Radios," *IEEE JSAC*, vol. 26, no. 1, Jan. 2008, pp. 146–55.

[60] K. R. Chowdhury and M. D. Felice, "SEARCH: A Routing Protocol for Mobile Cognitive Radio Ad-Hoc Networks," *Comp. Commun. J.*, vol. 32, no. 18, Dec. 2009, pp. 1983–97.

[61] C. Xin, B. Xie, and C. Shen, "A Novel Layered Graph Model for Topology Formation and Routing in Dynamic Spectrum Access Networks," *Proc. IEEE DySPAN*, Nov. 2005.

[62] K. R. Chowdhury, M. D. Felice, and I. F. Akyildiz, "TP-CRAHN: A Transport Protocol for Cognitive Radio Ad-Hoc Networks," *Proc. IEEE INFOCOM*, Apr. 2009.

[63] O. B. Akan and I. F. Akyildiz, "ATL: An Adaptive Transport Layer Suite for Next-Generation Wireless Internet," *IEEE JSAC*, vol. 22, no. 5, 2004, pp. 802–17.

[64] S. Gandhi *et al.*, "A General Framework for Wireless Spectrum Auctions," *Proc. IEEE DySPAN*, Apr. 2007.

[65] X. Zhou *et al.*, "eBay in the Sky: Strategyproof Wireless Spectrum Auctions," *Proc. ACM MobiCom*, Sept. 2008.

[66] J. Jia, Q. Zhang, and M. Liu, "Revenue Generation for Truthful Spectrum Auction in Dynamic Spectrum Access," *Proc. ACM MobiHoc*, May 2009.

[67] Q. Zhao *et al.*, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework," *IEEE JSAC*, vol. 25, no. 3, Apr. 2007, pp. 589–600.

[68] FCC, "Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking," ET Docket No. 04-167, Sept. 2004.

[69] H. Kim and K. G. Shin, "Optimal Admission and Eviction Control of Secondary Users at Cognitive Radio Hotspots," *Proc. IEEE SECON*, June 2009.

[70] J. Jia and Q. Zhang, "Competitions and Dynamics of Duopoly Wireless Service Providers in Dynamic Spectrum Market," *Proc. ACM MobiHoc*, May 2008.

[71] D. Grandblaise *et al.*, "Microeconomics Inspired Mechanisms to Manage Dynamic Spectrum Allocation," *Proc. IEEE DySPAN*, Apr. 2007.

[72] R. Chen, J.-M. Park, and J. H. Reed, "Defense Against Primary User Emulation Attacks in Cognitive Radio Networks," *IEEE JSAC*, vol. 26, no. 1, Jan. 2008, pp. 25–37.

[73] Y. Liu, P. Ning, and H. Dai, "Authenticating Primary Users' Signals in Cognitive Radio Networks Via Integrated Cryptographic and Wireless Link Signatures," *Proc. IEEE Symp. Security and Privacy*, May 2010.

[74] N. Goergen, T. C. Clancy, and T. R. Newman, "Physical Layer Authentication Watermarks Through Synthetic Channel Emulation," *Proc. IEEE DySPAN*, Apr. 2010.

[75] P. Kaligineedi, M. Khabbazian, and V. K. Bharava, "Secure Cooperative Sensing Techniques for Cognitive Radio Systems," *Proc. IEEE ICC*, May 2008.

[76] A. W. Min, K. G. Shin, and X. Hu, "Attack-Tolerant Distributed Sensing for Dynamic Spectrum Access Networks," *Proc. IEEE ICNP*, Oct. 2009.

[77] R. Chen, J.-M. Park, and K. Bian, "Robust Distributed Spectrum Sensing in Cognitive Radio Networks," *Proc. IEEE INFOCOM*, Apr. 2008.

[78] USRP: Universal Software Radio Peripheral, http://www.ettus.com.

[79] W. Xu, P. Kamat, and W. Trappe, "TRIESTE: A Trusted Radio Infrastructure for Enforcing Spectrum Etiquettes," *Proc. Allerton*, Sept. 2008.

[80] S. Liu *et al.*, "ALDO: An Anomaly Detection Framework for Dynamic Spectrum Access Networks," *Proc. IEEE INFOCOM*, Apr. 2009.

[81] K. A. Woyach *et al.*, "Crime and Punishment for Cognitive Radios," *Proc. Allerton*, Sept. 2008.

[82] C. R. S. *et al.*, "IEEE 802.22: The First Cognitive Radio Wireless Regional Area Network Standard," *IEEE Commun. Mag.*, Jan. 2009, pp. 130–38.

[83] A. Stirling, "White Spaces — the New Wi-Fi?," *Int'l. J. Digital Television*, vol. 1, no. 1, 2010, pp. 69–83.

[84] S. Deb, V. Srinivasan, and R. Maheshwari, "Dynamic Spectrum Access in DTV Whitespaces: Design Rules, Architecture and Algorithms," *Proc. ACM MobiCom*, Sept. 2009.

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