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DYNAMIC SPECTRUM ACCESS: FROM COGNITIVE RADIO TO NETWORK RADIO

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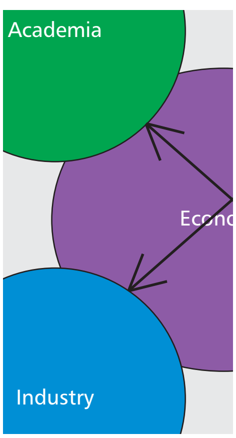

DSA is a promising technology to alleviate the spectrum scarcity problem and increase spectrum utilization. The authors discuss the challenges of DSA and aim to shed light on its future.

ABSTRACT

Dynamic spectrum access is a new spectrum sharing paradigm that allows secondary users to access the abundant spectrum holes or white spaces in the licensed spectrum bands. DSA is a promising technology to alleviate the spectrum scarcity problem and increase spectrum utilization. While DSA has attracted many research efforts recently, in this article, we discuss the challenges of DSA and aim to shed light on its future. We first give an introduction to the state-of-the-art in spectrum sensing and spectrum sharing. Then, we examine the challenges that prevent DSA from major commercial deployment. We believe that, to address these challenges, a new DSA model is critical, where the licensed users cooperate in DSA and hence much more flexible spectrum sharing is possible. Furthermore, the future DSA model should consider the political, social, economic, and technological factors all together, to pave the way for the commercial success of DSA. To support this future DSA model, the future cognitive radio is expected to have additional components and capabilities, to enforce policy, provide incentive and coexistence mechanisms, etc. We call the future cognitive radio with the expanded capabilities a network radio, and discuss its architecture as well as the design issues for future DSA.

INTRODUCTION

Traditionally, the spectrum allocation policy grants a fixed spectrum band to a licensed user for exclusive access. While this policy has worked well in past decades, the proliferated wireless services in recent years have unveiled the drawback of this policy: it results in *spectrum scarcity*. On the other hand, a significant amount of licensed spectrum is considerably underutilized in both the temporal and spatial domains. These unused spectrum bands in the temporal and/or spatial domain, called *spectrum holes* or *white spaces*, offer a great opportunity for wireless communications. Dynamic spectrum access (DSA) is a new spectrum sharing paradigm that utilizes the spectrum holes and hence alleviates the spectrum scarcity problem as well as increases spectrum utilization. With DSA, secondary users (SUs) dynamically search for idle spectrum bands, and temporarily access them for wireless communications. To avoid interference to primary users (PUs), SUs continuously monitor the spectrum bands and yield to PUs whenever PUs start using a band.

DSA is made possible by recent advances in cognitive radio technology. A cognitive radio typically consists of an analog RF front-end, and a digital processing engine, which may be a general-purpose processor, a digital signal processor (DSP), or a customized field programmable gate array (FPGA) board. Most radio functions such as signal processing are implemented through software running on the digital processing engine. Through programming the digital processing engine, cognitive radio can sense the surrounding spectrum environment and accordingly adapt radio parameters such as the center frequency, bandwidth, transmit power, and waveform to utilize spectrum bands currently not used by PUs.

Due to its great promise to improve the efficiency of spectrum utilization, there have been extensive research efforts in DSA and cognitive radio in last decade. There are also quite a few surveys on cognitive radio or DSA networks, e.g., see [1]. While these survey studies primarily focus on network design problems for cognitive radio networks, in this article, we discuss the challenges of DSA and aim to shed light on its future. We first introduce the state of the art in spectrum sensing and spectrum sharing. Then we focus on discussing the challenges that prevent

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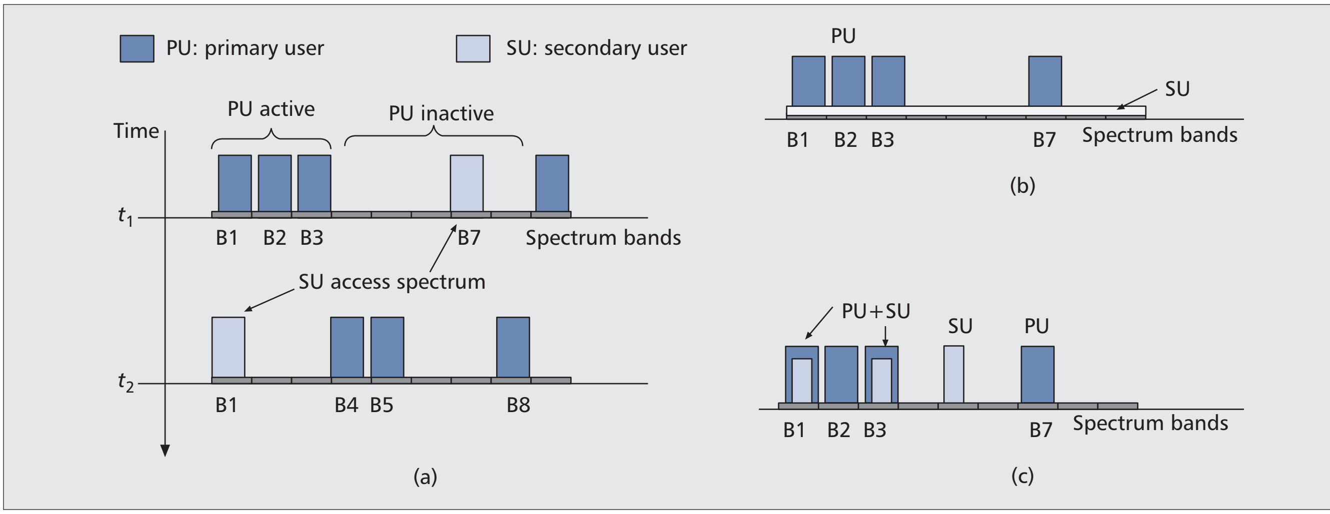

Figure 1. *DSA models: a) interweave DSA model; b) underlay DSA model; c) overlay DSA model. In the interweave DSA model, an SU can transmit only on a spectrum band where the PU is not active, and has to jump onto different bands over time. In the underlay DSA model, an SU can transmit on a spectrum band no matter the PU is active or not, but at a low power on each band to limit interference. In the overlay DSA model, an SU can transmit on a spectrum band with a large power even when the PU is active.*

DSA from major commercial deployment. We believe that, to address these challenges, a new DSA model is critical, where PUs are incentivized to cooperate in DSA, and hence flexible spectrum sharing is possible. For example, spectrum sensing can be much simplified, and SUs are allowed to transmit on a spectrum band simultaneously with PUs. Furthermore, the future DSA model should consider the political, social, economic, and technological factors all together. To support the future DSA model, additional components and capabilities are needed to enhance the current cognitive radio. We call the future cognitive radio with the expanded capabilities a *network radio*.

The remainder of the article is organized as follows. We introduce the DSA models. We discuss spectrum sensing, and describe spectrum sharing and access. We discuss the current challenges of DSA and possible breakthrough. We describe our vision to the future DSA and network radio. We then conclude the article.

Dynamic Spectrum Access (DSA) Models

There are three DSA models, interweave, underlay, and overlay [2], illustrated in Fig. 1. The interweave DSA model is the one predominantly studied in the literature, and the de facto standard for DSA. It is different from the overlay and underlay DSA models in that an SU cannot access a licensed spectrum band as long as a PU is active on the band. Furthermore, the PU has the absolute priority on the spectrum band, and an SU that is accessing the spectrum band must yield to the PU whenever the PU starts to access the band. Hence, the interweave DSA model is also called *opportunistic spectrum access* in that SUs are constrained to opportunistically utilize the spectrum holes or white spaces in the temporal, spatial, and/or frequency domain. With the interweave DSA model, an SU uses the cognitive radio to sense the surrounding spectrum environment, then selects one or more idle spectrum band(s), and switches the cognitive radio to the selected band(s) to transmit. Figure 1a illustrates the dynamics of spectrum availability and how SUs search and access idle spectrum bands with the interweave DSA model.

The underlay DSA model allows SUs to transmit on a licensed spectrum band regardless of the PU accessing the band or not, subject to a constraint that the accumulated interference from all SUs is tolerable by the PU, i.e., below some threshold. There are two approaches to meet this constraint. In the first approach, the SU transmit power spreads over a wide range of spectrum such that the interference to the (narrowband) PU on each licensed band is well below the threshold. This is the approach taken by the ultra-wide band (UWB) technology. This approach is primarily for short range communications. The second approach is called *interference temperature*. With this approach, SUs can transmit with a higher power on a licensed spectrum band, as long as the total interference from all SUs on the band is below a threshold. The challenge is how to measure the total interference to the PU and how to impose this constraint on SUs. Due to this challenge, the Federal Communications Commission (FCC) has tabled the interference temperature approach. Figure 1b illustrates how an SU shares a wide range of spectrum with PUs on each band, in the underlay DSA model.

The overlay DSA model is a more recent development of DSA. Similar to the underlay DSA model, the overlay DSA model also allows SUs to transmit on a licensed spectrum band even when the PU is accessing the band. However, the constraint is different. Instead of constraining the interference from SUs to PU through limiting the transmit power of SUs, the overlay DSA model targets maintaining the PU performance. SUs are allowed to transmit simultaneously with PUs as long as there is no performance degradation for PUs. The first approach for the overlay DSA model is to use channel coding [2]. Specifically, when a PU transmitter is transmitting a PU packet that is known to an SU transmitter, the SU transmitter can split its transmit power into two parts, one to transmit its own (SU) packet, and the other to transmit the PU packet to enhance the total power received at the PU receiver, such that the signal to interference and noise ratio (SINR) at the PU receiver does not degrade. Moreover, the SU transmitter can use the dirty paper coding to precode the SU packet, so that the interference to the SU receiver caused by the PU packet transmission is cancelled. Another approach for the overlay DSA model is to use network coding [3]. With this approach, an SU serves as a relay node between disconnected or weakly connected PU nodes. While relaying a PU packet, the SU may encode an SU packet onto the PU packet through network coding, and hence the transport of the SU packet does not incur separate spectrum access, without degrading the PU performance.

One noticeable property of the overlay DSA model is that it can offer incentive to PUs for cooperating in DSA. With the channel coding approach, an SU transmitter may split enough power to transmit the PU packet such that the SINR at the PU receiver is increased. Thus, PU performance is effectively improved. With the network coding approach, it is possible to increase the transmission data rate, and a higher PU throughput is possible (see [3] for details). In conclusion, the overlay DSA model creates a "win-win" situation for both PUs and SUs. Figure 1c illustrates how SUs share spectrum with PUs in the overlay DSA model.

Spectrum Sensing

Spectrum sensing plays a critical role in DSA. Before an SU transmits a packet, it needs to sense the spectrum environment to identify an available spectrum band. During the packet transmission, an SU needs to continuously sense the band to detect if there is a PU accessing the band.

Spectrum sensing techniques can be generally classified as local sensing and cooperative sensing. Local sensing means that each SU independently senses the surrounding spectrum environment and then selects an idle spectrum band for communications. There are three major techniques for local sensing, energy detection, matched filter detection, and cyclostationary feature detection. In energy detection, the received signal energy is measured and compared with a pre-defined threshold. The spectrum band is determined to be occupied by a PU if the received signal exceeds the threshold; otherwise the spectrum band is determined to be idle. The energy detection technique has low computation complexity and is easily implemented. However, it is vulnerable to the uncertainty of noise power, and cannot distinguish between noise and signal. The matched filter detection technique assumes that the knowledge of the PU signal is known a priori, e.g., the modulation type and order, pulse shaping, and the packet format. It correlates the received signal with the known PU signal, and samples the output at the bit rate to detect the presence of the PU. To distinguish between noise and signal, the cyclostationary feature detection technique has been proposed (e.g., see [4]). This technique arises from the fact that most modulated signals are characterized by the cyclostationary feature, since their means and autocorrelations exhibit periodicity. In addition to the three major techniques, several other techniques have been developed recently. For example, the eigenvalue technique uses the eigenvalues of the covariance matrix of the signals received at SUs for spectrum sensing [5].

While local sensing is important, many studies have shown that local sensing is often not sufficient to provide accurate detection due to the effect of fading, shadowing, and other issues in the complicated wireless environment. As such, cooperative sensing has been proposed to improve the detection accuracy through cooperation among SUs. Cooperative sensing can be implemented in either a decentralized mode or a centralized mode [6]. In the decentralized mode, SUs exchange local sensing data/results with each other, and then each SU makes its own decision on the channel accessibility. In the centralized mode, a fusion center such as a base station is commonly employed to collect sensing results from all SUs. The fusion center then makes decision on the channel accessibility.

Spectrum Sharing and Access

Efficient spectrum sharing and access is essential to DSA. It has received considerable attention from both researchers and policy-makers. Spectrum sharing in the underlay DSA model is the most flexible provided that the interference constraint is met. Spectrum sharing in the overlay DSA model is also flexible, but has some limitations. Specifically, when an SU tries to transmit an SU packet, if the PU performance can be guaranteed to not degrade, then the SU can access the licensed spectrum. Otherwise, the SU needs to yield to PUs for spectrum access.

Spectrum sharing under the interweave DSA model is much more challenging, because this model forbids SU spectrum access when a PU is accessing the spectrum. The studies on spectrum sharing in the literature are predominantly for the interweave DSA model (e.g., see [7, 8]). In DSA, the communication channels (spectrum bands available for SU access) are dynamically available, which raises a great challenge for spectrum sharing and access under the interweave DSA model. There are primarily two approaches depending on whether a control channel is available. In the first approach (e.g., see [8]), a common control channel is used for coordination among SUs to exchange spectrum sensing results and negotiate a data channel. The spectrum access of SUs generally works in a sensing-transmission cycle. During the sensing period, each SU senses the surrounding spectrum environment to identify spectrum bands available for SU communication, and then switches its radio to the control channel to exchange sensing

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results with other SUs. (SUs are typically assumed synchronized). Each communication node pair then negotiates a *data channel* for data communication from the detected available channels, and finally switches their radios to the selected data channel to transmit data packets. The SUs continuously monitor the data channels, and whenever a PU signal is detected on a data channel, the SUs on this channel must yield to the PU.

While a common control channel does streamline rendezvous between the transmitter and the receiver in spectrum access, it is vulnerable to congestion and jamming. The ETCH algorithm proposed in [9] uses multiple control channels to avoid congestion while guaranteeing that an SU can meet any other SU within a frame of optimal length.

Another approach does not use control channel at all and hence eliminates congestion and jamming on the control channel [10]. With this approach, every SU independently chooses its operational channel from the dynamically detected channels. A communication pair does not need to exchange control messages, e.g., to negotiate the channel for data communication. Instead, the transmitter estimates the operational channel of the receiver, and simply switches the radio to the receiver's channel. It has been shown that the success probability of channel estimation is high, and hence the transmitter can meet the receiver with a high probability.

Although the majority of studies on spectrum sharing for the interweave DSA model is at the MAC layer, i.e., assuming a single-hop network, there have been quite a few studies on spectrum sharing in multi-hop DSA networks as well, e.g., see [11, 12]. With multi-hop DSA networks, the user demands are end-to-end communication sessions, each between a source and a destination. The spectrum sharing becomes more challenging as it is typically coupled with other problems such as spectrum allocation, scheduling, routing, etc. The objective is to optimize some utilities, such as the network-wide radio spectrum usage [11] or power consumption [12], while satisfying all user demands. Such a problem is usually NP-hard, and hence effective heuristic algorithms are needed. For instance, the authors in [11] developed a near-optimal algorithm that can obtain performance close to the lower bound of the optimization objective.

It is worthy to point out that most studies on spectrum sharing in the literature consider the sharing between PUs and SUs. The spectrum sharing between SUs, in particular between SUs from coexisting DSA networks, has attracted little attention. However, this problem is very important for the success of DSA, because with the potentially large portion of spectrum available to DSA, it is expected that a large number of DSA networks would coexist in the same area. With the high density and the availability of spectrum with good propagation feature, it is critical to design effective coexistence mechanism for DSA networks to reduce interference and improve the effective utilization of spectrum.

Current Challenges and Breakthrough of DSA

While the research efforts in last decade have shown great potential for DSA, it is still far from major commercial deployment. The research and development activities are primarily limited to academia, with deployments primarily experimental testbeds. The industry interest is limited to simple approaches such as geo-location database approach, rather than the more general spectrum sensing based approaches. Such simple approaches cannot exploit the full potential of DSA, and more importantly, are only applicable to spectrum bands with special features, e.g., the TV bands. In this section, we discuss the challenges to DSA (primarily the interweave DSA model which is the de facto standard), and discuss possible solutions.

Challenges to DSA

Using today's technology, the spectrum sensing and sharing under the predominant interweave DSA model are very challenging. Since in this DSA model, an SU cannot access a spectrum band if there is a PU signal on the band. An SU has to accurately detect the existence of a PU signal. However, accurate spectrum sensing is very challenging, due to the effect of multipath, fading, shadowing, and the ever growing pollution level of radio interference. Cooperative spectrum sensing can help alleviate some of these problems, but cannot completely eliminate them. In addition, new problems arise, including complicated control and coordination, concerns on freshness of the sensing data/results due to the exchange delay, increased decision making time, and security concerns since malicious SUs can intentionally mislead the final decision by reporting fake (incorrect) sensing data.

There are also other issues for spectrum sensing. The inherent uncertainty of noise makes it challenging to differentiate between signal and noise. The authors in [13] pointed out that there exists an "SINR wall," and below a certain SINR wall, the matched filter, energy, and feature detection would all fail to distinguish noise from signals. Many spectrum sensing techniques, such as matched filter detection, feature detection, etc., rely on prior knowledge of PU waveforms or special features, such as a pilot signal. However, the PU waveform on a spectrum band may change and the special features may disappear, due to spectrum repurposing, spectrum trading, or upgrading to new technology. Furthermore, when an SU is transmitting, it has to continuously sense the spectrum band to detect if a PU signal appears during the SU transmission. If so, then the SU is required to immediately vacate the band even though SU is in the middle of transmission. Such a stringent requirement not only causes significant overhead, but also disrupts SU transmission, making SU communication highly unstable and unpredictable, and hence results in a poor quality of service. Moreover, due to the requirement that an SU must yield to a PU whenever the PU starts to access the spectrum band, the SU is vulnerable to the primary user emulation (PUE) attack. The PUE attack happens when a malicious SU transmits the PU waveform on a spectrum band through its cognitive radio, which emulates a PU signal and hence prevents other SUs from accessing the spectrum band. The PUE attack is unique to DSA networks and very difficult to be detected and counter-measured. With all of these issues, the economical return for the industry to invest on DSA is uncertain. Together, the uncertainty of technical advance and economical return prevents potential service providers and vendors to consider large scale investments on DSA technologies, devices, and infrastructure.

In addition to the challenges from the technical point of view, perhaps the bigger challenges come from the inter-play between different players for DSA: policy-maker, academia, industry, and end-users. As shown in Fig. 2, all four players influence each other, and the key component connecting them together is the economy. Policies will not be changed unless

- There is a critical need
- Science and technology are ready to make a change

The future DSA model must consider the political, social, economic, and technological factors altogether. In the rest of the section, we discuss how the interplay between the technology and the policy can provide a possible breakthrough for DSA.

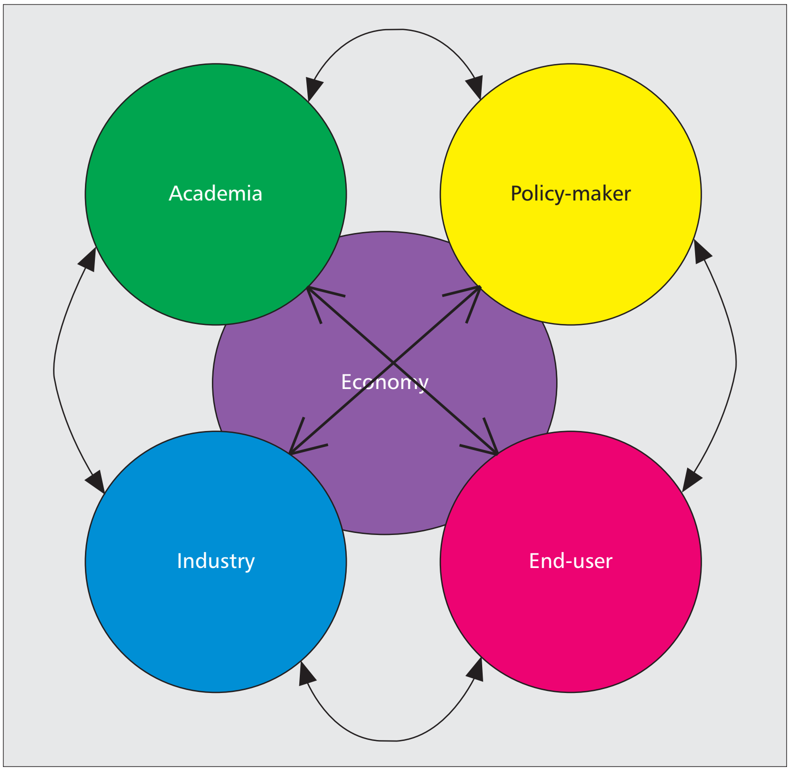

Figure 2. *The interplay between DSA players and the challenges.*

Breakthrough of DSA

To make breakthroughs in DSA, it is worthy to revisit the interweave DSA model with regard to the following fundamental questions.

- Is it cost-effective to build a cognitive radio following the current interweave DSA model? Is it worthy to build and use such a radio for DSA that has significant overhead for spectrum sensing, spectrum vacating, and handoff?
- Should we continue to assume such a DSA model, when the spectrum regulation is at a stage of rapid changes? The spectrum policy is changing and now it is possible to "force" some PUs to give up some or all of their spectrum bands, or cooperate in DSA, e.g., via partial relief of spectrum fee (to be discussed). Do we still have to use the rather conservative interweave DSA model?

A major problem of the interweave DSA model is lack of an incentive mechanism for PUs to cooperate in DSA. In fact, PUs have an inherent hostility toward DSA, because they are concerned with the interference from SUs due to miss-detection in spectrum sensing, underestimation of SU interference, incorrect configuration of radio parameters, etc. To eliminate the hostility of PUs toward DSA, it is critical to design an incentive mechanism to compensate PUs for them to cooperate in DSA. With the compensations, PUs can be cooperative in DSA and hence it is possible to significantly reduce the technical challenges and to facilitate the deployment of DSA networks.

We believe that it is possible to break through the conservative interweave DSA model, from both technical and policy aspects. From the technical aspect, the overlay DSA model is a promising alternative to the interweave DSA model. It provides incentives to both PUs and SUs, as the PU performance can be improved with the help of SUs, while SUs can access spectrum simultaneously with PUs. Hence the overlay DSA model is promising to eliminate most challenges raised by the interweave DSA model. However, there are still many limitations in current approaches for the overlay DSA model. For example, current approaches focus on how PUs and SUs share spectrum on a channel. It may still need spectrum sensing for the SUs to find good candidate channels for DSA, although the technical complexity for spectrum sensing can be reduced, because in this case, the objective is to evaluate which channel has a better chance to obtain higher performance. Moreover, network coding does not always have significant gain, and it also incurs extra overhead and complexity. Lastly, for the channel coding approach, the power consumption may need to increase. Therefore, further research on the overlay DSA model is needed to propose more practical and effective approaches.

From the policy side, the spectrum authorities (FCC and the National Telecommunications and Information Administration (NTIA)) are also considering incentive mechanisms to improve the spectrum efficiency and expand access to licensed spectrum bands. For instance, the Incentive Subcommittee of the Commerce Spectrum Management Advisory Committee is proposing *spectrum fee* as an incentive mechanism from the policy perspective. The license holder of a spectrum band will need to pay a spectrum fee for the use of the spectrum band. As one effect, the license holders that use their spectrum bands at a low level or consider their spectrum bands of little value are expected to "donate" all or part of their spectrum bands, in exchange for a spectrum fee reduction. These donated spectrum bands

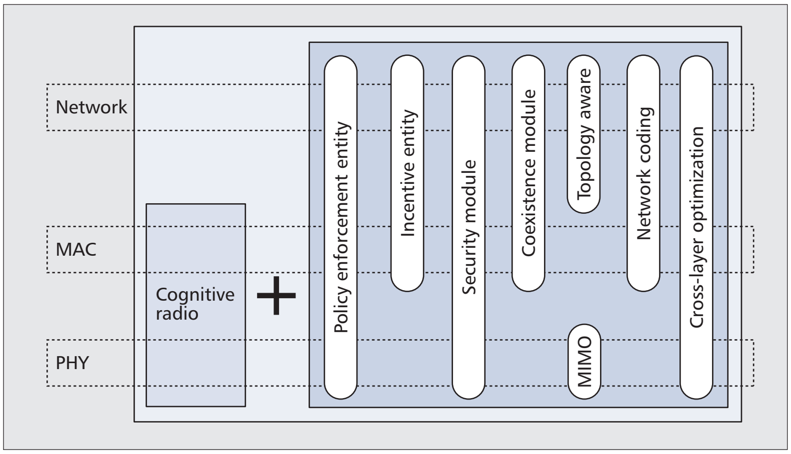

Figure 3. *The architecture of future DSA and network radio.*

can then be repurposed for more flexible DSA. As another effort, the Incentive Subcommittee also considers establishing a *spectrum innovation fund* using the revenue from spectrum auctions, as well as collected spectrum fees. Such a fund can be used to compensate certain license holders to make them more cooperative in DSA, e.g., by allowing more flexible DSA to the unused or little used spectrum capacity.

Allowing simultaneous access of spectrum between SUs and PUs would also alleviate the impact of the PUE attack, which is a serious security problem for the interweave DSA model. Since an SU is allowed to transmit at the same time as the PU, the SU does not need to vacate the band even if there is a PU signal, which effectively eliminates the PUE attack. As another example, a cooperative PU can make some changes to help spectrum access by SUs,[1] e.g., having a database of real-time activity, transmitting a pilot signal or periodic beacons to alert SUs. Yet another example is in femtocells, where femtocells (SUs) can listen to macrocell (PUs) control channel information.

Future DSA: from Cognitive Radio to Network Radio

Future DSA model is expected to meet diverse interests, ranging from the policy-maker's interest of maximizing the revenue to the end-user's quality of experience. Therefore, the cognitive radio, which is the enabling technology for DSA, is expected to be more powerful in the future. We envision that future cognitive radio would have four more components: policy enforcement entity, incentive entity, security module, and coexistence module; and four more capabilities: network topology awareness, network coding, cross-layer optimization, and multiple-input-multiple-output (MIMO), as illustrated in Fig. 3. The policy enforcement entity ensures that the DSA policies such as specrum usage rules are enforced. With the incentive entity, PUs are incentivized to explicitly or implicitly provide information on channel activity to significantly reduce the overhead on spectrum sensing. Furthermore, SUs may be allowed to transmit simultaneously with PUs, as long as they can protect PU performance to a desirable degree. The security module enables the radio to effectively alleviate attacks such as PUE. With the coexistence module, PUs and SUs, and SUs from different domains and technologies can cordially coexist on a spectrum band. Moreover, due to the dynamics of spectrum availability, the cognitive radio needs to be aware of the DSA network topology to ensure high performance and quality of service. Network coding would add additional capabilities to cognitive radio to capitalize on interference and offer incentives to PUs and SUs. The cognitive radio will also be capable of conducting cross-layer optimization so that the spectrum sensing and channel switching are coordinated with the network topology formation and adaptation, to optimize the network-wide or end-to-end performance and quality of service. In addition to boosting throughput, MIMO technology would enable the cognitive radio to conduct flow-level resource allocation and performance optimization.With these additional entities and capabilities, the cognitive radio would expand its capability from a primarily physical layer technology to a network technology. We term the future cognitive radio with these additions as *network radio*, to emphasize this technology expansion. Briefly speaking, the network radio will be able to implement incentive mechanisms and spectrum policy dynamically, facilitate the coexistence of multiple DSA networks with possible different technologies, enforce security policies across all users and devices, coordinate the topology formation and adaptation, carry out cross-layer optimization, and apply MIMO and network coding to optimize performance.

There are many design issues for the future DSA. For example, the following is a short list:

- The design of PU cooperation mechanisms and the trade-off analysis. What type of PU cooperation is most useful and practical, e.g., explicit or implicit? How frequently should such cooperation be provided? What metrics should be considered?
- The performance metrics considered by the incentive mechanism. The current work on the overlay DSA, based on channel coding and network coding, primarily focuses on PU throughput. Other metrics should also be considered, such as PU network stability, delay, and user experience.
- Hardware design and implementation. With the 500 MHz national broadband plan, the cognitive radio will be required to be able to operate over hundreds of megahertz and tune within a range at the order of tens of GHz.
- Economic models. Instantaneous monetary incentive, such as license tax, is necessary, but may not be sufficient. One should also consider more sophisticated economic issues such as competition and the risk of SU investment over a time horizon of years or decades.

Conclusion

In this article, we have briefly reviewed dynamic spectrum access (DSA), and discussed the current challenges faced by DSA. We believe that to address these challenges, it is critical that the

[1] *While it is not legitimate to simply require a PU change the existing technology and infrastructure to facilitate spectrum sensing, as the PU may have already invested billions of dollars in the infrastructure, it is possible to do so by providing incentive to the PU.*

future DSA model offers incentives to PUs and SUs, so that PUs cooperate in DSA and hence spectrum sharing can be more flexible, e.g., SUs can access spectrum simultaneously as PUs. To support the future DSA model, the cognitive radio is expected to have several additional entities and capabilities, which would essentially expand the cognitive radio from a physical layer technology to a network technology. We have termed such cognitive radio as network radio, to emphasize this technology expansion. We have also briefly discussed the design issues associated with the future DSA and network radio. The new DSA model has many challenges as well as great potentials. Its immediate applications could include HetNet (heterogeneous networks), which is considered in LTE-A where cells of different sizes coexist. Its long-term application could be the future of wireless communications.

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To support the future DSA model, the cognitive radio is expected to have several additional entities and capabilities, which would essentially expand the cognitive radio from a physical layer technology to a network technology.