# Dynamic Spectrum Access: Current State of the Art and Future Challenges

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***Abstract*—Dynamic Spectrum Access (DSA) is emerging as a promising technology to mitigate the spectrum scarcity caused by static frequency allocations. Despite the clear need for more efficient allocation, however, DSA faces a number of challenges, chief among them being the perceived risk of interference to incumbent systems. In this paper, we present an overview of DSA technology, including the current state of research and applications. We then recommend areas of focus that would address the challenges. They include the need for quality-of-service (QoS) guarantees, associated metrics, and prototype implementations that demonstrate and validate the predicted benefits.**

## I. Introduction

Spectrum scarcity due to strict, exclusive, and static allocation of frequency bands is a growing problem. Dynamic Spectrum Access (DSA) is a promising technology that can address this problem. In DSA, primary users (PUs) are the licensed (or intended) users of the spectrum. In addition to the PUs, secondary users (SUs) can dynamically use the same spectrum as long as they do not cause significant performance degradation for the PUs.

Researchers have worked on various aspects of this relatively new technology and have generated important results which can be useful in development of products in this space. However, despite the impressive theoretical research output, there has been less progress on the implementation of prototypes and test environments to validate proposed solutions or on the translation of effective solutions to mature standards for interoperability.

In this paper, we first provide a brief overview of DSA, including the current state of research. We then highlight applications that have garnered interest and are particularly amenable to early adoption of DSA. After identifying some of the challenges this technology faces in terms of industry acceptance, we recommend areas of focus for the research and development community that would facilitate the adoption of DSA.

## II. Overview of DSA

We begin with an overview of the main components of DSA technology—the spectrum sharing model, sensing scheme, control channel architecture, and MAC protocol—and highlight some of the key work in each of these areas.

### A. Models for DSA

There are three models being used by researchers for dynamic spectrum access. These are *interweave*, *underlay* and *overlay* models. In the interweave model, the SU detects spectrum idle times and transmits during those idle periods (also known as *white space*). Thus, in this model, the SU opportunistically transmits only when the PU is silent. For this reason, this model is also referred to as *Opportunistic Spectrum Access* (OSA).

In the underlay model, the SU can transmit in the licensed band regardless of whether the band is being occupied by the PU or not. However, the SU transmits in such a way that the signal-to-noise ratio (SNR) at the PU receiver is above a given threshold such that the PU communication is not significantly affected. Usually, the SU spreads its transmit power over a wide spectrum so that the interference in the narrow band of the PU is minimal.

The overlay model is a relatively new concept. As in the underlay model, the overlay model also allows SUs to transmit simultaneously with the PUs such that the performance degradation of PUs is minimal, but the approach taken is different. There are primarily two methods used to achieve this: *channel coding* and *network coding*. In channel coding, the SU transmission consists of two parts: one is used for its own transmission whereas the other is used to send PU traffic so as to increase the signal power at the PU receiver [1]. When the network coding method is used, the SU acts as a relay node between the PU sender and receiver and encodes its own packet into the PU packet it relays [2].

### B. Sensing Schemes

Spectrum sensing is a critical part of a DSA system. SUs need to sense the medium to find available white spaces. Errors in sensing can cause performance degradation in PU or in SU systems. When the SU misses detecting the PU (called *missed detection*) and transmits, it causes interference to the PU. On the other hand, if the sensing result indicates presence of the PU when the spectrum is actually idle (called *false alarm*), then a transmission opportunity is lost and SU efficiency suffers.

Sensing schemes can be classified into three categories. The simplest method is *energy detection*. When the energy level in the spectrum is determined to be above the noise floor, the PU is assumed to be present. Although it is simple and less complex, it typically requires a higher SNR for detection.

*Matched filter* sensing relies on knowledge of some property of the PU signal, such as the modulation scheme, carrier frequency or pulse shape. It samples the received signal to detect the presence of the PU based on one or more of these properties.

*Cyclostationary feature detection* is a sensing technique used to detect known cyclostationary signatures in PU traffic [3]. But implementation of this technique is more complex and has more latency than energy based detection because it requires a large number of samples for better estimation.

Although these three categories capture the most widely used sensing techniques, a few other techniques have been reported in the literature. For example, the eigenvalues of the covariance matrix of the received signal can be used by the SU to detect the primary signal [4]. The Papyrus system detects a rising edge followed by a falling edge in the power spectrum to establish presence of a PU [5].

A DSA system may implement local sensing or cooperative sensing. Cooperative sensing provides better performance in the presence of fading, shadowing and hidden nodes. It exploits the spatial diversity among SUs to obtain better sensing results. But the improvement in performance is achieved at the cost of higher latency and communication overhead. Cooperative sensing can be implemented with distributed or centralized architectures [6].

### C. Control Channel Architecture

SUs in any DSA system need a control channel to share information required for communication, such as sensing results and channel information (e.g., which channel to use and when). Hence, a common control channel (CCC) over which to transmit this information is an integral part of a DSA system. There are primarily four types of CCC architecture.

In a *dedicated* CCC scheme, a channel is set aside for communication of control information. While it is simple to implement, it may not be adaptable to fluctuations in control traffic. If control channel traffic is low, then a static allocation could be a waste of resources. On the other hand, when the number of SUs increases, the channel may become congested. In *common hopping* CCC architecture, the SUs share a common hopping sequence to tune to the control channel. This architecture requires tight synchronization among the SU nodes. In *split phase* architecture, a frame is divided into two parts: control phase and data phase. In the control phase, SU nodes receive control messages. In the data phase, normal data transmission is performed. In *Multiple Rendezvous Control Channel* (MRCC), nodes hop over multiple channels until a common (or rendezvous) channel is found.

Researchers have also used *underlay* control channel for cognitive radios. In this architecture, the SUs communicate control information with wideband transmissions such that the energy level is below the PU's noise floor [7].

A detailed discussion on control channel schemes can be found in [8].

### D. MAC Protocols

MAC protocols in OSA networks are quite different from those in traditional wireless networks. In a traditional wireless network, a node has to share the medium with other nodes as a peer. A MAC protocol in an OSA network not only has to share the medium with its peers, but it also has to carefully schedule its access during the idle periods of PUs. Thus, OSA networks have a hierarchical (or tier) structure, where PUs are at a higher tier than the SUs.

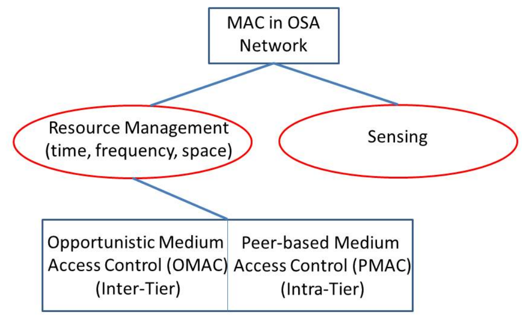


Fig. 1. Functional parts of OSA MAC

A MAC protocol in an OSA network has two main components, as shown in Fig. 1. The *Resource Management* module is responsible for allocating and scheduling resources (in time, frequency, and space) for the SUs per some desired goal, e.g., to maximize SU throughput. This module consists of two parts. The first part, *Opportunistic Medium Access Control (OMAC)*, manages competing demands for access by the PU and SU tiers. This part can be viewed as a preemptive priority based resource scheduler, where the PUs have higher priority than the SUs. Thus, SUs can access the medium when the PU is absent, but they should vacate the medium as soon as PUs appear. The difficulty in designing this part of the protocol is that SUs typically do not know when PUs may access the spectrum since there is usually no communication between the two tiers. The problem becomes more challenging because sensing can produce false alarms or missed detections. Fading and shadowing in the channels can also make PU detection more difficult. So, minimizing interference to PUs due to SU transmission is a challenge.

The second part of the Resource Management component is *Peer-based Medium Access Control (PMAC)*, which is responsible for coordinating access of multiple SUs to the medium. This part can be a traditional wireless MAC protocol, e.g., CSMA based or TDMA based, or it can be a specialized component designed for a particular OSA network.

The two components (OMAC and PMAC) of the Resource Management module can be designed together or separately. The choice depends on various factors such as deployment scenario, amount of information known about the PU network, number of channels in the PU network, target application of the SU network, and whether the SU network performance needs to be optimized. For example, if the SU network is meant to transmit light traffic occasionally (e.g., utility network meter reading), then optimization of SU network performance is not a major concern and hence the two functional parts can be designed separately. On the other hand, if the SU application has heavy traffic and hence wants to maximize its throughput in the PU network, then the two parts of the Resource Management component should be designed together.

Although, strictly speaking, sensing is a physical layer component, we show it in Fig. 1 as an integral part of OSA MAC, since resource management in an OSA network heavily depends on sensing results.

There are many MAC protocols presented in the literature for DSA networks. [9] provides a detailed survey and taxonomy of MAC protocols for DSA networks.

## III. Applications of DSA

This section discusses some of the applications of DSA, including one that has an enabling standard and others that hold promise for being early applications of DSA.

### A. TV White Space

In the US, the Federal Communications Commission (FCC) has ruled to allow unlicensed devices to operate in TV broadcast bands on an opportunistic basis. Since the bands are located in the ultra high frequency (UHF) and very high frequency (VHF) regions, they have good propagation characteristics. It is expected that a single TV white space base station can cover tens of kilometers. Thus, it can be used to provide coverage to a large campus. It is being viewed as a reliable technology for backhaul connectivity [10]. Especially in rural areas, where it is not feasible to lay cable and where the TV bands have low utilization, this technology carries a lot of promise.

The FCC ruling permitting the use of TV white space has led to the IEEE 802.22 standard for Cognitive Radio based Wireless Regional Area Networks (WRAN) [11]. This standard specifies that the WRAN system would use vacant channels between 54 MHz and 862 MHz while avoiding interference with the incumbent. Each WRAN cell has a base station (BS) and associated customer-premises equipment (CPE). Channel availability (white space information) can be determined via geolocation of the CPE and a database service, or by spectrum sensing, and is reported to the BS. The BS then schedules uplink transmissions based on this report. The standard provides mechanisms for incumbent detection, self-coexistence among overlapping IEEE 802.22 cells, and quality of service (QoS) to SU flows. More details can be found in [11].

The authors of [10] developed a campus-wide prototype of TV white space networking. The implementation used custom-built hardware based on the WiMax IEEE 802.16d chipset that operates on the VHF and UHF white space band. There were two base stations with backhaul connection to the Internet. One mobile node was set up inside a campus shuttle in which a PC acted as a WiFi Access Point on one interface and as a TV white space client (communicating with the base station) on another interface. Thus, users could seamlessly connect to the WiFi access point through their WiFi device, which in turn, connects them to the Internet through the TV white space base stations.

### B. Cognitive Femtocells

Cognitive femtocells represent an application of DSA that has a shorter timescale of adaptivity than TV white space. The greater temporal adaptivity stems from the nature of the primary user traffic in this application.

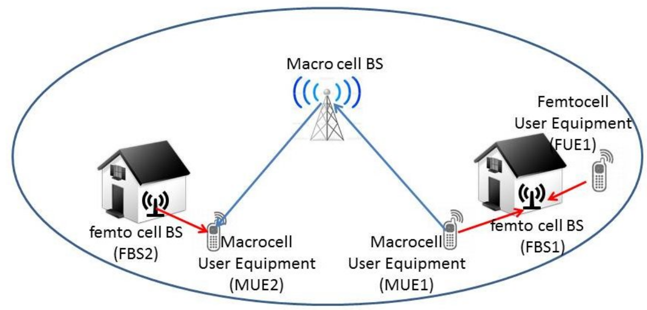


Fig. 2. Inter-cell interference between macro and femtocells

A femtocell is a low-power cell site in a mobile cellular network that is often used to provide improved indoor coverage in homes and offices. A femtocell is typically connected to the service provider's core network through the customer's Internet access connection. A key issue with femtocells is inter-cell interference with the nearby macrocell. This is depicted in Fig. 2. When user equipment (MUE1) served by the macrocell is located close to femtocell base station FBS1, its relatively high uplink transmission power can interfere with the uplink of user equipment (FUE1) served by the femtocell. Conversely, the femtocell base station FBS2's transmission can interfere with a nearby macrocell MUE2's downlink. The interference issue is particularly pronounced when the femtocell is of the *closed subscriber group* type, whereby access to the femtocell's air interface is restricted to certain users (e.g., the home's residents or the office's employees), essentially creating a coverage hole for other users. Solutions to mitigate intercell interference in so-called heterogeneous networks include allocating different radio access resources between femtocells and their nearby macrocells on a fixed basis [12].

A *cognitive* femtocell is a femtocell that intelligently and dynamically allocates air interface resources based on the usage of nearby macrocells [13]. The framework is essentially a DSA framework in which the macrocell is the primary user and the femtocell is the secondary user. The femtocell senses what time-frequency resources are in use by the macrocell and dynamically allocates resources such that it does not interfere with the macrocell's transmissions. Dynamic allocation offers greater flexibility and potentially improved spectral efficiency over fixed allocations. Given the strong interest in femtocells in the mobile networking industry, it is likely that cognitive femtocells will represent a key use of DSA technologies in coming years.

### C. Device-to-Device Communication

Another potential application of DSA in a mobile cellular network is device-to-device (D2D) communication. D2D is a direct mode of communication between nearby mobile devices that would otherwise be routed through the base station and associated infrastructure. It is envisioned as a means to offload traffic from potentially congested infrastructure as well as to provide communication opportunities in the absence of a link to the base station (e.g., deep indoor scenario). Interest in D2D has been spurred by the prospect of offering proximity-based services in commercial networks, such as media sharing and gaming. There is also interest in non-commercial networks. For example, the public safety community is accustomed to direct mode communication between emergency responders on its current networks. As this community migrates to broadband cellular networks, a D2D capability is being sought in order to preserve this critical mode of communication. The 3rd Generation Partnership Project (3GPP) has studied the feasibility of what it terms "proximity-based services" in preparation for inclusion in Release 12 of Long Term Evolution (LTE) specifications [14].

While D2D connections may be facilitated and controlled by the cellular network infrastructure [15], one could also envision a framework in which D2D connections are established in a decentralized fashion by the devices themselves. Such a framework would allow for D2D communication in the absence of a link to the base station, which is highly desirable in the public safety community, for example. In the decentralized scenario, the peer-to-peer network would function as a secondary network, sensing for and giving priority to the primary transmissions.

### D. Sensor Networks

Many types of sensor networks have light traffic requirements and may not justify the use of dedicated spectrum. One example is utility meter reading. Sensor data tends to be highly correlated and in many cases, such as meter reading, are tolerant to delay. Such low duty-cycle and delay tolerant applications are prime candidates for secondary access to shared spectrum.

### E. DSA in Unlicensed Spectrum

DSA can also play an important role in unlicensed spectrum. As more devices appear on unlicensed bands, it may become necessary to prioritize traffic. For example, it is common to have multiple WiFi devices in a home connected to the Internet through a single access point. Currently, they access the medium as peers. But it may be more appropriate to set priorities among the devices. For example, the device running a video streaming application may have a higher priority than the smart fridge reporting its temperature. Using DSA technology, the smart fridge can transmit its packets when it detects white space in the spectrum, rather than competing with the video streaming application.

## IV. Challenges and Opportunities

### A. Risk of Interference

While several applications of DSA are envisioned, the success of DSA, observe Chapin and Lehr [16], depends on a combination of technical, market, and regulatory factors. Outlining a technology cycle for the deployment of DSA-based services, they note that among the potential barriers to success is the perceived risk of interference to incumbent systems by DSA systems. As this perception of risk decreases, they argue, incumbent system operators are more likely to share their spectrum and regulators to make new shared spectrum available. The increased availability of shared spectrum creates additional opportunities for DSA services, which if successful, further reduces the perceived risk.

In view of the concern regarding interference, it is reasonable to expect that early applications of DSA in licensed spectrum will be owned or supplied by the same operator as the PU application (e.g., cellular network provider deploying cognitive femtocells). Such deployments may help to demonstrate the safe operation of DSA technology in friendly environments. Other early deployments of DSA may target simpler RF bands, such as TV white space, where the incumbent signal is not very dynamic in time or frequency. In these bands, the technical barriers to sharing the spectrum are lower.

In more challenging environments, or when the secondary system is operated by a different entity than the primary system operator, strong service level agreements from the secondary operator will likely be required by the primary operator. Such agreements will rely on the availability of metrics to measure disruption to the PU as well as OMAC protocols that can guarantee that agreed upon levels of disruption are not exceeded. The next section cites techniques that would support QoS guarantees to the PU.

### B. Disruption QoS

In OSA systems, SUs access the medium opportunistically when PUs are absent. In most cases, SUs would not know exactly when PUs will appear in the spectrum. Thus, typically there will be some disruption to the PUs in terms of interference. The OMAC should be designed to keep the disruption low. Some systems do not have a way to limit this disruption, whereas others are designed to provide bounds for disruption. We refer to the former as systems with *best effort* disruption and the latter as systems with *disruption QoS*.

One easy way to provide best effort disruption is to allow the SU to transmit for a *short* duration. The short duration has to be appropriately quantified in the context of a PU system (e.g., the average PU idle period). One good example of such a system is the Hardware-Constrained Cognitive MAC [17] which uses a fixed transmission duration, $T$, that is much shorter than the PU activity duration, to limit interference to the PU. There are many OSA MACs in the literature which do not specify how long an SU should transmit once it detects a white space (for example, see [18], [19]). They, too, can be considered as providing best effort disruption.

Obviously, schemes providing disruption QoS will be preferred over best effort disruption from the PU service provider's point of view. But providing disruption QoS is quite challenging, because the reappearance of the PU is not known a priori. SUs can use various methods to estimate PU traffic characteristics and predict when the PU might appear. A review of the literature finds that there are very few MACs which provide disruption QoS (e.g., [20], [21], [22]). The continued development and verification of protocols that provide disruption QoS may spur wider industry acceptance of spectrum sharing.

### C. Metrics

In order to judge the effectiveness of a DSA implementation, metrics are needed to measure both the effectiveness of the SU in exploiting spectrum opportunities as well as the impact on the PU. In the case of the former, such metrics can include the amount of information communicated on the secondary network (throughput, spectral efficiency), the latency of the information, and the reliability of the transfer (probability of error). Equally important, however, are the metrics for impact on the PU. These may include the probability of collision with the PU or the percentage of time an SU's transmission overlaps with a PU's transmission. Closer to the PU application layer, one could also consider the difference in throughput, latency, and reliability of the PU's transmission with and without the presence of the secondary network.

### D. Prototype Implementations

While a great deal of work on DSA has been reported in the research literature, actual implementations validating the claims are very few. Prototype implementations are needed to fill this gap. Fortunately, a number of platforms are available to facilitate DSA prototype development on software-defined radios (SDRs). Hardware options range from field-programmable gate arrays and digital signal processors to general-purpose processors, or combinations of these, paired with radio-frequency front-ends. Furthermore, software toolkits are available that provide building blocks for commonly used communication functions. A survey of SDR hardware and software platforms is provided in [23]. Prototype implementations and demonstrations would help build the required confidence to adopt DSA technology.

## V. Conclusion

We presented an overview of DSA technology, broad areas of research currently being carried out in this field, current and prospective applications of DSA, and the future challenges and opportunities this technology presents. To address these challenges, we recommend areas of focus for the research, development, and standards communities. They include continued development of protocols that provide disruption QoS to the primary network, the definition of metrics to quantify the impact on the primary user, and the demonstration of prototypes that validate the promised benefits and safeguards of DSA.

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