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Spectrum Sharing in Dynamic Spectrum Access Networks: WPE-II Written Report

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University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-09-11.

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Abstract

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Comments

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1 Introduction

In current wireless networks, the spectrum is regulated by governmental agencies, such as Federal Communication Commission (FCC) in United States, and is statically assigned to licensed users on a long term basis. For example, 824-849 MHz, 1.85-1.91 GHz, 1.930-1.99 GHz frequency bands are reserved for licensed cellular and personal communication services (PCS) and require a valid FCC license, whereas the most popular unlicensed bands are the Industrial, Scientific, and Medical (ISM) bands at 900 MHz, 2.4 GHz, and 5.8 GHz. Figure 1 shows a subset of current static spectrum assignment [8], ranging from sonic to ultra violet. Interested readers may refer to Appendix B for a more detailed current radio spectrum (3KHz - 300GHz) allocation in United States.

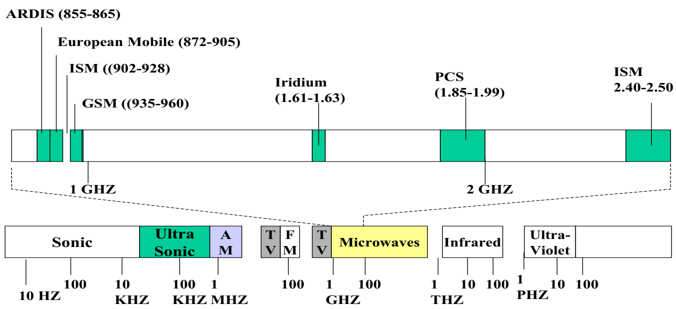

Figure 1: A subset of current spectrum assignment

However, a recent study by FCC [12] shows that most of the spectrum is, in practice, unused most of the time, while some spectrum is heavily used, as shown in Figure 2 [4]. For example, within ISM bands, anyone can transmit at any time, as long as their power does not exceed the band's regulatory maximum. This results that the ISM bands are crowded and may sometimes experience significant interference. Current limited availability and inefficient usage of spectrum necessitate a new communication paradigm. Recently software defined radio (SDR) [21] has been developed to enable on the fly changes to characteristics of radio such as power, modulation, and allows same hardware to be reconfigured for use in different parts of the radio spectrum. Based on the development of SDR, dynamic spectrum access (DSA) is proposed by researchers to solve spectrum inefficiency problems by allowing opportunistic spectrum access.

In DSA networks, there are two classes of spectrum users, which are primary and secondary users. Primary users already possess a license to use a particular frequency and always have full access to the spectrum when they need it. Secondary users could use the licensed/unlicensed spectrum opportunistically when it would not interfere with the primary user. DSA mainly consists of two components, which are *spectrum sensing* and *spectrum sharing*. Secondary users observe by sensing wide spectrum to find out which spectra are currently unused by primary users. After spectrum sensing, spectrum sharing assigns and schedules spectrum among secondary users. Compared to traditional radio, DSA can increase spectrum utilization and reduce wireless interference, hence improving network throughput, quality of service (QoS), etc.

Basically spectrum sharing can be formalized as a graph coloring prob-

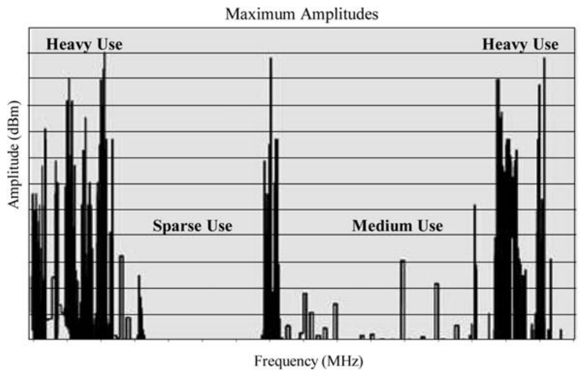

Figure 2: Spectrum utilization example

lem. Recently intense research efforts have been made towards spectrum sharing in DSA networks. Classified in different aspects, there are centralized versus distributed spectrum sharing by the architecture, cooperative versus non-cooperative spectrum sharing by cooperation behavior, with versus without common control channel, and single versus multiple radio interfaces, etc. DARPA started next generation (XG) program, which aims to build a DSA network for military usage. XG radios demonstrate for the first time that DSA networks are capable to utilize wide-range spectrum in realistic environments. Furthermore, a novel declarative policy engine for spectrum sharing is employed for XG.

Spectrum sharing plays a key role in DSA, since its design significantly affects the performance of DSA networks, such as interference level, network throughput. Efficient spectrum sharing is integral to the success of open spectrum systems, and there are still many challenges in spectrum sharing research. The purpose of this written preliminary exam (WPE) II report is to survey spectrum sharing techniques in DSA networks.

The rest of this report is organized as follows. Section 2 gives an overview of dynamic spectrum access and presents the motivation for why spectrum sharing is an important topic for research. Based on the taxonomy of spectrum sharing, we discuss centralized spectrum sharing in Section 3, and distributed spectrum sharing in Section 4 (with common control channel) and in Section 5 (without common control channel). Section 6 introduces DARPA's XG radios and its novel declarative policy engine for spectrum sharing, as well as its field test results. Section 7 reviews all the spectrum sharing techniques, and discusses challenges and future direction.

2 Overview

This section gives an overview of dynamic spectrum access and its two main components — spectrum sensing and spectrum sharing. Spectrum sharing is the focus of this report thus we outline its basic problem statement and motivations why it is important for DSA.

2.1 Dynamic Spectrum Access

In the early 1990s, Joseph Mitola first introduced the idea of software defined radios (SDRs) [21]. Different with traditional radio, SDR enables on the fly changes to characteristics of radio such as power, modulation, and waveform, and allows same hardware to be reconfigured for use in different parts of the radio spectrum. SDR is an integral technique for DSA since it enables the usage of temporarily unused spectrum referred to as *spectrum hole* or white space [14], as shown in Figure 3 [4]. Compared to traditional radio, DSA can significantly increase spectrum utilization by coordinating the spectrum usage among secondary users, thus reducing potential interference, and improving network throughput and quality of service (QoS), etc. The applications of DSA networks include cognitive ad hoc network (e.g. WNaN [2]), emergency network, military network(e.g. XG [1]), IEEE 802.22 [3], etc. DSA shares some similarity with multi-channel 802.11 MAC [11, 29], in that they both allow users to opportunistically access different parts of spectrum. However, there are significant differences between them. DSA has the advantages that it can utilize the whole spectrum and while incurring no interference to primary users. More differences are discussed in Appendix A.

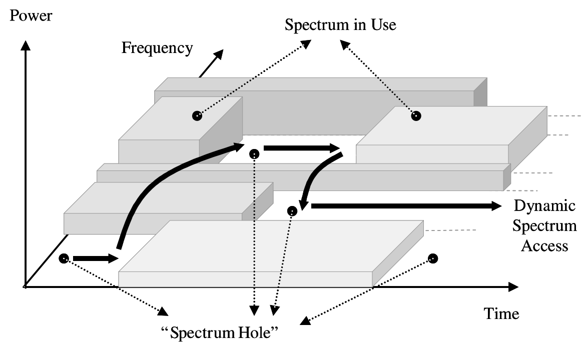

Figure 3: The concept of spectrum hole

As introduced in Section 1, wireless networks have primary and secondary users. The goal of DSA is the coexistence of primary and secondary users [1] and the most important challenge is to share the licensed spectrum without interfering with primary users. Typically DSA has two components, which are spectrum sensing and spectrum sharing. Figure 4 shows the position of spectrum sensing and spectrum sharing in TCP/IP stack model. Spectrum sensing and spectrum sharing are mainly located at the physical and the link layer, respectively. Spectrum sensing keeps scanning a wide range of spectrum and periodically reports spectrum information to spectrum sharing. We note that spectrum sharing involves with part of network layer. This is because network layer issues (such as routing) can be taken into consideration in spectrum sharing.

[1] In the remaining parts of this report, under the premise of causing no confusion, we use the term *user/node* to specifically refer to secondary user/node in DSA networks.

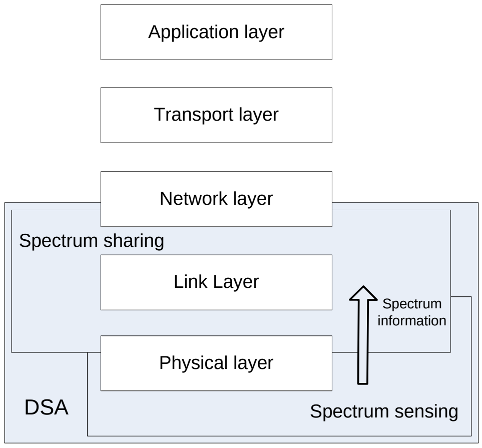

Figure 4: Spectrum sensing and spectrum sharing in the TCP/IP stack model

2.2 Spectrum Sensing

Spectrum sensing is primarily a physical (PHY) layer issue, which aims at finding out spectrum holes for secondary users when coexisting with primary users. In spectrum sensing, hardware capable of tuning to any part of a large range of frequency spectrum (typically 5MHz to 6GHz) enables real-time measurements of spectrum occupancy and interference level. There has been intense research activities made for spectrum sensing [30, 18]. However, since spectrum sensing is not our focus of this report, we only introduce the simplest spectrum sensing technique, which is called *energy threshold based detection*. Other techniques such as *cooperative detection*, *matched filter detection* and *interference based detection* [4] are omitted for brevity.

Energy threshold based approach uses observed power (or lack of it) in a band as a proxy for whether interference in this band is detrimental to operation of the primary users [25]. The energy threshold is set to some value (by experiment or experience), and secondary users turn on their radio interfaces to sense a wide range of spectrum. When sensed signal strength is beyond the threshold, the presence of primary users at that specific spectrum is considered to be positive, and the secondary users will mark the spectrum as occupied and evacuate immediately from that spectrum.

2.3 Spectrum Sharing

After spectrum sensing, secondary users obtain the information of available spectrum, and the next step in DSA is spectrum sharing. Spectrum sharing is mainly located in the MAC layer (see Figure 4) and is used to schedule spectrum assignment among secondary users. Spectrum sharing involves with spectrum allocation, spectrum access and spectrum mobility (switch from one spectrum to another). Spectrum sharing plays a key role in DSA, since its design greatly affect the performance of DSA networks.

2.3.1 Problem Statement

In single-channel wireless networks, since the medium is broadcast based and shared among all nodes, interference could happen when more than one packet is received by a node at the same time. Although multiple access protocol such as CSMA/CA [9] requires the nodes to sense the channel before transmitting, interference is still possible due to the hidden terminal problem [15, 6]. RTS/CTS type MAC protocols [15] was proposed to solve hidden terminal problem, however, there is still " multi-channel hidden terminal problem" in multi-channel environment, as shown in Figure 5 [29]. In dynamic spectrum access networks, with well designed spectrum sharing, problems similar to"multi-channel hidden problem" can be eliminated. E.g. in the scenario of Figure 5, spectrum sharing may require node C to listen on the control channel during the channel negotiation of node A and B. In short, by opportunistically utilizing spectrum holes, spectrum sharing can increase spectrum utilization and reduce wireless interference.

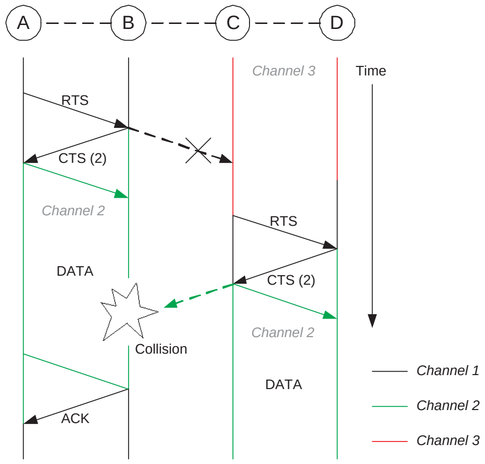

Figure 5: Multi-channel hidden terminal problem: Channel 1 is the control channel. Since C was listening on one of the data channels when B sent a CTS, C does not know about communication between A and B [29].

Spectrum sharing can be formalized as an graph coloring problem if we assume that there are totally K channels (Channel $C_1, C_2, ..., C_K$) for secondary users and all channels have same radio range. Suppose there are totally N secondary users indexed as $1, 2, ..., N$. We use $U_n \subseteq \{C_1, C_2, ..., C_K\}$ to denote the available channels for user n and $L_{n,m}$ to denote the available channels for the link between node n and m, for $n, m \in \{1, 2, ..., N\}$, then

$$L_{n,m} = U_n \cap U_m \tag{1}$$

If we map each single-hop link to a vertex, a network topology F can be converted to a conflict graph G [31]. In G an edge exists between two vertices if the corresponding links can not be active concurrently. Two links sharing a common node conflict with each other, and will have an edge in between. In addition, links in close proximity will interfere with each other if they are assigned with the same channel. These links are also connected with edges.

When coloring each vertex of G, $L_{n,m}$ is the set of candidate colors to use. Once G is colored, we get a corresponding spectrum assignment, i.e. the program of spectrum sharing can be transfered to a equivalent graph coloring problem. Normally, to avoid interference, the constraint of coloring G is that any two vertices that have an edge in between can not use the same color, which is: for each $L_{n,m}$, there is a channel assignment $A_{n,m} \in L_{n,m}$, so that

$$A_{n,m} \neq A_{m,p} \quad n, m, p \in \{1, 2, ...N\}. \tag{2}$$

If the graph coloring constraint can not be satisfied (no feasible solution) and there are any two connecting vertices using the same channel (color), then it falls back to single-channel multiple access. There could be various optimization goals for coloring G, such as minimizing the total number of colors, maximizing link throughput, maximizing network throughput, etc. The goal of minimizing total number of colors can be written as:

$$minimize\{the\ size\ of\ set\ \{A_{n,m}\}\} \tag{3}$$

Additionally, we note that when the goal is to minimize the total number of colors and the candidate color set $L_{n,m}$ is same (homogeneous network) for each vertex, then the problem falls back to a normal graph coloring problem [17]. In general, graph coloring with optimization goals is $NP-hard$ in complexity. The conflict graph G needs to be updated and re-colored once there is any change in network topology or available spectra. Figure 6 shows an network topology example and the available channels of each secondary user, with a total set of available channels $\{C_1, C_2, C_3, C_4, C_5, C_6\}$. Figure 7 shows its conflict graph G in which available channels for each link are labeled aside. Table 1 lists spectrum assignment schemes for graph coloring. If the goal of graph coloring it to minimize the total number of colors, then Scheme 2 is the best one.

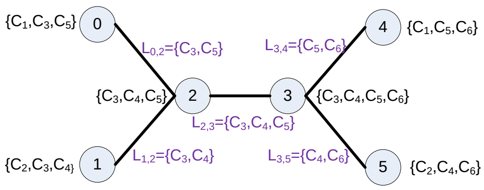

Figure 6: An network topology with available channels labeled aside each user

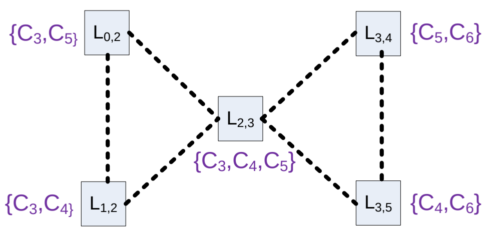

Figure 7: Conflict graph G of the network topology in Figure 6

Vertex	$L_{0,2}$	$L_{1,2}$	$L_{2,3}$	$L_{3,4}$	$L_{3,5}$
Scheme 1	C_3	C_4	C_5	C_6	C_4
Scheme 2	C_5	C_4	C_3	C_5	C_4
Scheme 3	C_5	C_4	C_3	C_6	C_4
Scheme 4	C_5	C_4	C_3	C_5	C_6
...	...	...	...	...	...

Table 1: Channel assignment schemes for the network topology in Figure 6

2.3.2 Taxonomy

There has been intense research on spectrum sharing, in this report, we classify spectrum sharing techniques according to four categories shown in Figure 8, which are:

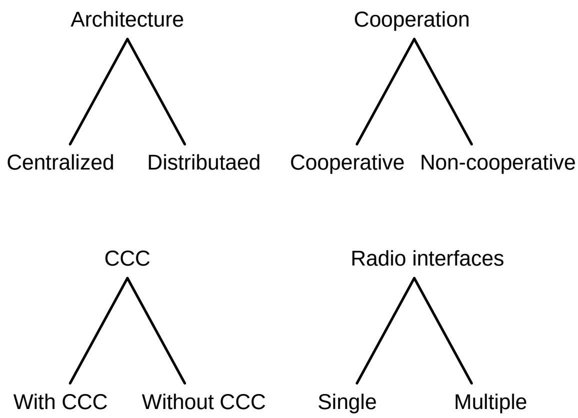

Figure 8: Classification of spectrum sharing based on architecture, cooperation behavior, CCC and radio interfaces

(1) **Architecture**, whether it is *centralized* or *distributed*. In centralized spectrum sharing, a centralized entity have a global view of the network and controls all the spectrum allocation procedures [7, 8, 26, 33]. Distributed spectrum sharing has such no infrastructure [19, 34, 35, 36, 1, 25].

(2) **Cooperation behavior**, whether it is *cooperative* or *non-cooperative*. In cooperative spectrum sharing [7, 19, 34, 1], users communicate with each other to exchange locally observed interference measurements, while in non-cooperative spectrum sharing [27, 36, 35, 25], nodes allocate spectrum only based on its local observations of interference patterns. Non-cooperative spectrum sharing may result worse performance in spectrum utilization, throughput and fairness [22], though the communication overhead can be reduced compared to cooperative spectrum sharing [36].

(3) **Common control channel (CCC)**, *with CCC* or *without CCC*. CCC is a specific control channel predefined for all secondary users to communicate control information with each other. The control information includes spectrum assignment, spectrum negotiation, spectrum time scheduling, etc. The use of CCC can simplify the design of DSA networks [7, 19, 8], however, the indefin-

ability of spectrum in DSA networks may result a very low probability that an CCC can actually exist [34]. Moreover, CCC has saturation problem [5], and is vulnerable to security attack such as jamming. Therefore, various designs without CCC are proposed [34, 25, 1].

(4) **Radio interfaces**, *single* or *multiple*. With multiple radio interfaces, the design of spectrum sharing can be simplified [7, 19], however the cost of DSA network devices will be higher than single radio interface design [34, 1, 25]. In single radio interface, all traffic (control and data) must be scheduled carefully through the only radio interface, thus increasing the design complexity. With multiple radio interface, traffic may be transmitted and received at the same time, thus increasing the throughput compared to single radio interface.

Other categories, such as inter-network or intra-network [4], single or multiple hop consideration (upper layer issues such as routing [4]) may also be applied to classify spectrum sharing techniques. However, in this report, we only discuss intra-network spectrum sharing techniques which do not consider upper layer issues.

Due to space limit there is no possibility that we can go through all related literatures in spectrum sharing in this report. We are going to focus on some representative ones. Those techniques include: (1) dynamic spectrum access protocol (DSAP) [7]; (2) dynamic open spectrum sharing protocol (DOSS) [19]; (3) heterogeneous distributed MAC protocol (HD-MAC) [34]; and (4) DARPA's XG radios (XG) [20, 10]. Other related papers include Split Wideband Interferer Friendly Technology (SWIFT) [25], DIMSUMnet [8], etc. In Table 2, we outline these spectrum sharing techniques according to our proposed taxonomy.

Category	**Sub-Category**	**System**
Architecture	Centralized	DSAP, DIMSUMnet
	Distributed	DOSS, HD-MAC, XG, SWIFT
Cooperation	Cooperative	DSAP, DIMSUMnet, DOSS, HD-MAC, XG
	Non-cooperative	SWIFT
CCC	With CCC	DSAP, DIMSUMnet, DOSS
	Without CCC	HD-MAC, XG, SWIFT
Radio interfaces	Single	HD-MAC, SWIFT
	Multiple	DSAP, DIMSUMnet, DOSS, XG

Table 2: Taxonomy of spectrum sharing

3 Centralized

3.1 Overview

In centralized spectrum sharing [7, 8, 26, 33], a centralized entity possesses detailed information about the network and handles with all the spectrum allocation and access procedures. Hence, compared to distributed, centralized approaches simplify the design of spectrum sharing. Among centralized spectrum techniques, dynamic spectrum access protocol (DSAP) [7] is a representative one and is the focus of this section.

3.2 Architecture

DSAP enables dynamic spectrum access through a coordinating central entity and allows efficient resource sharing and utilization in a limited geographical environment. A typical architecture of DSAP is shown in Figure 9 [7]. DSAP consists of client, server, and relay. DSAP client collects local observations of spectrum usage by spectrum sensing and reports the information to DSAP server. From the spectrum information received from clients, DSAP server constructs a global view of network called *RadioMap*. DSAP client can not choose a wireless communication channel arbitrarily, instead it has to request appropriate channel assignment from DSAP server. DSAP server accepts communication requests from clients, and based on various optimization goals mentioned in Section 2.3.1 and the set of administration-defined policies and the *RadioMap* determine an "optimal" distribution of radio spectrum among the clients in the network and reconfigures the clients accordingly. Under different optimization goals, various algorithms and policies can be applied in the procedure of obtaining the optimal distribution of radio spectrum. After deciding spectrum assignment, DSAP server responds back with an time-bound spectrum allocation, call a *lease*. Lease may be revoked by the server, relinquished by the client or expire due to timeout. DSAP server has at least two wireless interfaces. One interface always operates on a pre-defined common control channel (CCC), which is used for exchanging control traffic between server and client. The other interface is used for actively reaching clients. DSAP relay allows multi-hop communication between server and client that are not in direct range of each other.

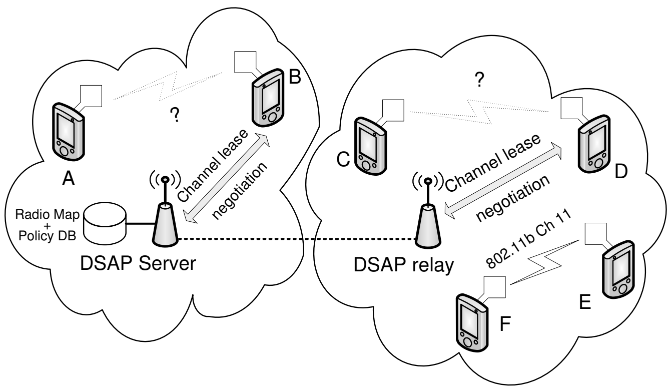

Figure 9: Architecture of DSAP

A typical procedure for DSAP client to acquire a new lease of spectrum is as follows [7]. Suppose a client wants to initiate communication with another client and requests an appropriate channel from the DSAP server. *ChannelDiscover* message is broadcast to any DSAP server in vicinity. Based on optimization goals, policies, and its RadioMap, DSAP server will respond with a *ChannelOffer* message. There may be more than one DSAP server in the vicinity of a client, to increase robustness for instance. Hence, it is possible that each server makes a ChannelOffer to the requesting client. Therefore it is required that the client picks only one of these offers for its own use through a *ChannelRequest* message to the appropriate server, thereby implicitly declining offers from all others. Finally the DSAP server will respond with a *ChannelACK* confirming (or denying) the channel lease request.

Similar to DSAP, DIMSUMnet(dynamic intelligent management of spectrum for ubiquitous mobile access network) [8] is a also centralized mechanism based on spectrum brokering that manages large portions of spectrum and assigns portions of it to individual domains or users. DSAP and DIMSUMnet are complementary to each other, in the sense that DSAP acts as a spectrum broker for heavily-used, densely-populated localized areas while DIMSUMnet is for a relatively large geographic regions.

3.3 Evaluation

According to the taxonomy in Table 2.3.2, spectrum sharing of DSAP is centralized, cooperative, with CCC and multiple radio interfaces. As one of the first spectrum sharing protocols, DSAP is typical and representative among centralized techniques. We summarize the strengths and limitations of DSAP (or general centralized spectrum sharing techniques) as follows.

Strengths:

- Since in centralized spectrum sharing the centralized entity owns all network information and performs the whole spectrum allocation procedure, various optimization goals in Section 2.3.1 and policies can be applied just in the centralized entity alone, without worrying anything about other client nodes. Moreover, the optimization goals and policies are independent with the architecture of DSA networks in centralized spectrum sharing. Hence, compared to distributed approach, centralized approaches significantly simplify the design of spectrum sharing. This can be deemed as the biggest advantage of centralized spectrum sharing.
- DSAP is able to handle non-compliant devices easily: when detrimental behaviors (from misconfigured/malicious devices) are detected by DSAP server due to broadcast nature of the wireless medium, DSAP server can reconfigure compliant clients to minimize negative effects. This property can be generalized to centralized spectrum sharing. In distributed spectrum sharing, non-compliant devices are much harder to deal with.

Limitations:

- Centralized design may be better for many practical environment, such as homes and offices. However, when there is no infrastructure available, such as in military network (e.g. XG [1]), centralized spectrum sharing is simply not feasible. For such scenarios, distributed design is more preferable. Moreover, centralized approach limits the scalability of DSA networks, since as the network size grows, the centralized entity may be overwhelmed with huge amount of computation tasks. We will go through distributed spectrum sharing in Section 4 and Section 5.
- DSAP client and server communicate through CCC. However, a CCC may not exist at all for secondary users due to the indefinability of DSA networks [34]. Moreover, there are saturation and security problem with CCC [5]. We will survey spectrum sharing techniques without CCC in Section 5.

- DSAP server requires multiple radio interfaces, which on one side simplify the design of the way client and server communicate, but on the other side increase the devices cost compared to single radio interface.

4 Distributed with CCC

4.1 Overview

As mentioned in Section 3, distributed spectrum sharing does not require any centralized entity or infrastructure, instead users self-organize and decide (cooperatively or non-cooperatively) the spectrum assignment due to changing environment. Hence distributed spectrum sharing is more scalable, which is suitable for military network (e.g. XG [1]), emergency network, etc. Research activities in distribute spectrum sharing techniques include [7, 19, 34, 1] (co-operative) and [27, 36, 35, 25] (non-cooperative). In this section we focus on Dynamic Open Spectrum Sharing (DOSS) protocol [19], which is a representative one for distributed spectrum sharing and uses common control channel.

4.2 Architecture

DOSS offers real time dynamic spectrum allocation and high spectrum utilization without aid of any infrastructure [19]. In DOSS, after detecting the presence of primary users, three channels are going to be setup — a predefined common control channel (CCC), a data channel and a busy tone channel. The common control channel is for negotiating incoming data channel transmission. Control traffic are exchanged among users through CCC. The busy tone channel is an extension of [13] for solving the hidden and exposed terminal problem. A linear one-to-one mapping between the data channel (high bit rate) and the busy tone (low bit rate) is used. DOSS requires at least two transceivers: one for data and control channel, one dedicated for busy tone.

During DOSS's spectrum sharing procedure, negotiation messages are exchanged through the common control channel. The sender (i.e. transmission initializer) sends a REQ packet over the common control channel to the intended receiver. A REQ packet contains the channel parameters (frequencies, bandwidth, etc.) of available spectrum observed by the sender. By listening to busy tones through the dedicated transceiver and referring to the spectrum mapping, the sender has full knowledge of the spectra being used for data receiving within its neighborhood, thus being able to avoid interference to other receivers. The receiver compares senders available spectrum with its own available spectrum, and picks up an intersection that is available to both. The receiver then replies with an acknowledgment (called REQ ACK), which contains the channel parameters of the negotiated data channel, over the control channel. If there are multiple dynamic channels available, the receiver will simply choose the one with highest frequency. The receiver refers to the spectrum mapping to find and turn on the corresponding busy tone in the dedicated transceiver, telling its neighbors not to send over this data channel. Upon receiving the REQ ACK, the senders knows the dynamic data channel over which the receiver is waiting for the data packet, and tunes its data transmitter to that channel for data transmission. Figure 10 [19] shows the procedure of spectrum negotiation in

DOSS protocol.

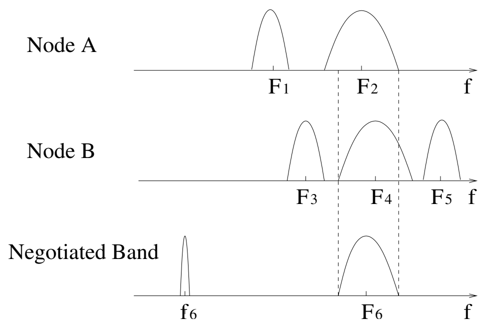

Figure 10: Spectrum negotiation in DOSS protocol: Node A is the sender, and Node B is the receiver. Channel $F6$ is the intersection of available spectrum of A and B, and is selected as the data channel for incoming data transmission. Channel $f6$ is the busy tone mapped from Channel $F6$.

4.3 Evaluation

According to the taxonomy in Table 2.3.2, DOSS is distributed, cooperative spectrum sharing with CCC and multiple radio interfaces. We summarize the strengths and limitations of DOSS as follows.

Strengths:

- Resulted from its distributed nature, DOSS does not require any central entity or infrastructure and is more scalable compared to centralized spectrum sharing. Moreover, the design of DOSS is simplified by the use of multiple radio interfaces and CCC.
- By employing a busy tone on a dedicated transceiver, the constraints (no interference) of the graph coloring problem are satisfied naturally 2.3.1. The hidden and exposed terminal problems are eliminated in DOSS. However, DOSS only consider single-hop based spectrum negotiation and does not apply any optimization goals for spectrum sharing.

Limitations:

- DOSS requires at least two transceivers: one for data and control channel, the other dedicated for busy tone. As mentioned in Section 2, more radio interfaces will increase device cost. What is more, besides normal spectrum sensing, DOSS sender needs to listen to to busy tones of other receivers to prevent possible interference, thus imposing additional overhead.
- Although DOSS proposes several techniques to mitigate the CCC saturation problem, such as limiting the traffic going through CCC and allowing slow migration of CCC traffic to current data channel, CCC is still vulnerable to security attack and has the potential to become a single point of failure. In Section 5 we will discuss spectrum sharing techniques without CCC.

5 Distributed without CCC

5.1 Overview

Spectrum sharing techniques introduced in previous two sections both use a predefined CCC. It is clear that a CCC facilitates many spectrum sharing functionalities such as transmitter receiver handshake, communication with a central entity, or sensing information exchange. However, there are inherent problems with CCC: (1) since secondary users may observe spectrum heterogeneity (i.e. available spectrum is different for different users), it is possible that no common channel exists at all [34]. Figure 11 shows an example spectrum system where a CCC is impossible; (2) although some CCC mitigation techniques have been devised as in DOSS [19], CCC's fixed bandwidth limits scalability of DSA network in terms of device density, traffic, etc; (3) CCC is vulnerable to security attack and may become a single point of failure. A simple jamming attack to CCC would disrupt the entire DSA network.

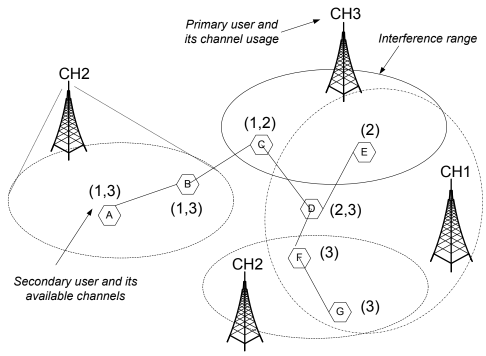

Figure 11: An example open spectrum system showing the impossibility of a CCC

Based on above observations, distributed spectrum sharing techniques without CCC have been proposed, such as heterogeneous distributed MAC (HD-MAC) [34] and SWIFT [25]. In this section we focus on discussing HD-MAC and how it manages to do spectrum sharing without a CCC.

5.2 Architecture

In HD-MAC, due to lack of CCC, secondary users self-organize into groups based on similarity of available spectrum. Members of each group form a mini multi-hop network and coordinate using a within-group control channel adaptively. Bridge nodes relay traffic between groups by switching between different spectrum according to time. There are two main parts in HD-MAC, which are group setup & maintenance and coordination procedure.

5.2.1 Group Setup & Maintenance:

To form HD-MAC mini groups, secondary users in HD-MAC periodically broadcast beacons rotating through available channels and do spectrum scanning to obtain spectrum availability information about their neighbors. After neighbor discovery, each device has a list of its neighbors, their available spectrum, and a schedule of time to connect to each of them. Hence users are able to send messages to all of its neighbors. Based on these information, a recursive distributed voting process [34] is performed to select a within-group control channel, where each user votes for a channel that provides the largest connectivity — the number of neighbors sharing the same channel.

HD-MAC periodically performs network-wide group reconfiguration to deal with network mobility, e.g. joining and leaving of users. When a primary user starts to occupy a control channel, affected secondary users need to evacuate immediately from the channel and reorganize themselves by negotiating another control channel.

5.2.2 Coordination Procedure

To support the coordination among secondary users without CCC, HD-MAC modified the legacy MAC protocol developed for IEEE 802.11 devices with multi-channel and single interface [29]. In legacy MAC protocol [29] transmissions are divided into super-frames, each consisting of a beacon broadcast (BEACON), a coordination window (CHWIN) and a data transmission period (DATA). In HD-MAC, legacy BEACON is modified to accommodate global beacon broadcast and group beacon broadcast. Global beacon broadcast is rotated among its available channels in subsequent super-frames for discovery of new users. Group beacon broadcast is persistently transmitted on the within-group control channel. In legacy MAC, CHWIN is a dedicated control window to disseminate coordination information. During CHWIN, users switch to the common control channel to solicit transmissions and negotiate the channel to use. HD-MAC modifies the CHWIN structure to allow bridge nodes to access multiple coordination groups in each super-frame. The CHWIN for bridge users is segmented into multiple slots, one for each within-group control channel. Figure 12 shows the super frames in HD-MAC compared to legacy MAC.

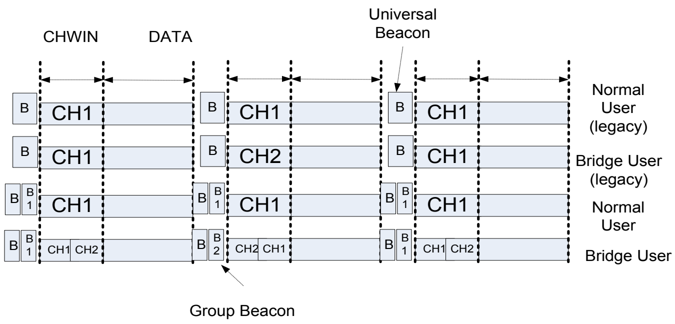

Figure 12: HD-MAC operation time line

The legacy MAC protocols in general keep a single FIFO queue to accumulate traffic for all the neighbors. Because there is head-of-line blocking problem [16] with single FIFO queue (i.e. it is possible that the current channel selected to send data packets is not available to the neighbor whose packets are at the head of the queue), HD-MAC proposes that each user employs a per-neighbor queue structure that assigns one FIFO queue for each neighbor to solve the head-of-line blocking problem.

Compared to the optimization goals of the graph coloring scheme in Section 2.3.1, HD-MAC proposes a novel metric for data channel selection, which jointly considers traffic load and interference level. In user u, the metric W for channel c is given in (4) [34].

$$\omega_u(c) = \lambda_{in} Q_{in}(c) + \lambda_{out} Q_{out}(c) - \lambda_f Q_f(c) \tag{4}$$

In (4), $Q_{in}(c)$ and $Q_{out}(c)$ represents the estimated volume of incoming and outgoing traffic over channel c, respectively, and $Q_f(c)$ is the estimated volume of traffic that would interfere over channel c. $Q_{out}(c)$ can be estimated from the queue length, and $Q_{out}(c)$ and $Q_f(c)$ can be estimated from neighbor's queue length. Similar to the channel negotiation procedure in DOSS, the sender u and receiver v will choose the intersection c of their available spectra, which maximizes $min\{\omega_u(c), \omega_v(c)\}$.

5.3 Evaluation

According to the taxonomy in Table 2.3.2, spectrum sharing of HD-MAC is distributed, cooperative, without CCC and with single radio interface. We summarize the strengths and limitations of HD-MAC as follows.

Strengths:

- Not dependent on a CCC is the most significant strength of HD-MAC, which improves scalability. By organizing users into groups, coordination messages are distributed onto multiple within-group control channels. This can prevent disruptions due to coordination traffic congestion and also security issues.
- Compared to the deign using multiple radio interfaces in DSAP and DOSS, HD-MAC only requires single radio interface, which reduces the device cost.
- HD-MAC can deal with network mobility, i.e. joining and leaving of nodes. During mobility, the network will perform group maintenance and re-organize into new groups.
- Experiments on ns-2 with CMU wireless extensions show that HD-MAC outperforms spectrum sharing approaches with CCC especially when the traffic load is high.

Limitations:

- Since a CCC and multiple radio interfaces are lacked in HD-MAC, legacy MAC protocol needs to be modified to support control traffic information exchange within and between groups. These modifications include changes to BEACON and CHWIN, and adding per-neighbor FIFO queue to avoid head-of-line blocking problem. Moreover, HD-MAC requires tight time synchronization among users when exchanging control traffic. Hence HD-MAC increases the design complexity for spectrum sharing.
- In HD-MAC neighbor discovery takes longer time compared to approaches with CCC, since secondary users periodically broadcast beacons rotating

through all available channels and do spectrum scanning to obtain spectrum availability information about their neighbors. Also, spectrum sharing overhead in HD-MAC is higher compared to the ones with CCC and multiple radio interfaces due to selection of within-group control channels and group maintenance.

6 DARPA XG Radios

6.1 Overview

Although plenty of spectrum sharing techniques have been proposed by the research community as introduced in previous sections, nearly all evaluation experiments are performed either in simulation software, or in unrealistic environments (e.g. in experiments of DSAP [7], switching between two IEEE 802.11 wireless cards are used to "simulate" spectrum mobility). On the other hand, in current radios such as DSAP [7], DOSS [19], HD-MAC [34], spectrum sharing policies are programmed or hard-wired into radio using imperative language (such as C) and form an inseparable part of the radio's firmware [10]. However, due to the large number of spectrum's operating dimensions to be considered (e.g. frequencies, power levels) and the ever-changing nature of environments and application requirements, it is not feasible to design and implement optimal algorithms that always allow radios to flexibly make use of available spectrum over time.

The U.S. Department of Defenses (DoD) Defense Advanced Research Projects Agency (DARPA) started Next Generation (XG) program [1, 20, 10], which employs a *declarative* policy engine for spectrum sharing [10, 24] and is demonstrated capable of using spectrum over a wide range of frequencies in realistic operational frequency-agile devices. XG declarative policy engine is a flexible mechanism that supports spectrum sharing while ensuring that radios will adhere to regulatory policies and is able to adapt to changes in policies, applications, and radio technology. In this section, we focus on XG's declarative policy engine for spectrum sharing and also its field test results.

6.2 Declarative Policy Engine

Figure 13 shows the architecture of XG declarative policy engine, which mainly consists of two components — the System Strategy Reasoner (SSR), and the platform-independent Policy Reasoner (PR).

SSR is a module typically specific to the radio hardware and can perform low-level tuning and real-time optimizations. The SSR is responsible for interacting with the PR for determining spectrum access opportunities that are currently available. The SSR then executes applicable strategies needed for the radios transmissions to conform to the policies [24]. PR allows encoding of spectrum-sharing policies, ensures radio behavior that is compliant with policies, and allows policies to be dynamically changed. The SSR must not transmit unless it has received message from the PR that the transmission is allowed.

A domain-specific, logic-based declarative language called Cognitive Radio Language (CoRaL) is employed in PR for expressing spectrum sharing policies. CoRaL is a typed fragment of first-order logic with equality, enriched by build-

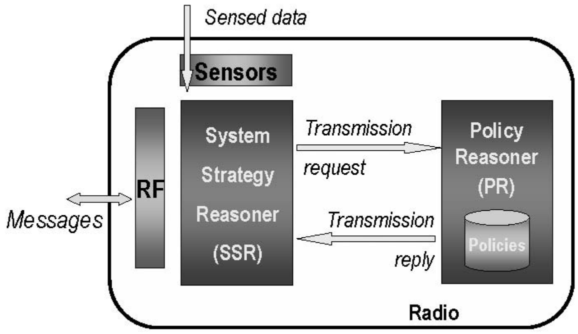

Figure 13: The architecture of XG declarative policy engine

in and user-defined concepts. Policy rules such as *allow* (permissive), *disallow* (restrictive) are logical axioms that express under which conditions these predicates hold. The policy rules may consider the radios capability, current state, location, time, and spectral environment for allowing a transmission. A concrete example of policy rule [10] is shown below, which says that the specified frequency ranges available (225.0-328.6MHz or 2200.0-2290.0MHz) is allowed for transmission, when the radio is in *Day-to-Day* or *TestingAndTraining* mode and has sensed signals of less than 115 dBm.

```
policy fixedMobile is
  use request_params;
  use mode;
  use region;
  allow if
    (centerFrequency(req_transmission) in {225.0 .. 328.6}
    or
    centerFrequency(req_transmission) in {2200.0 .. 2290.0})
  and
  (mode(Day-to-Day) or mode(TrainingAndTesting))
  and
  ((exists ?se:SignalEvidence)
    req_evidence(?se) and
    peakRxPower(?se) =< 115.0);
```

There are several advantages of declarative spectrum sharing over imperative approaches: (1) Declarative language is high level, which expresses "what" to do instead of "how". It allows designers to think about the requirements and targets without worrying about lower-level implementation details; (2) Independence. In the declarative policy engine, policy definition and radio implementation are decoupled. Devices and policies can evolve independently over time without worrying about each other. (3) Flexibility. As technological advances lead to an increasing number of radio designs, declarative policies can be dynamically changed and loaded without the need to recompile any software on the radio, compared to imperative approaches; and (4) Extensibility. A policy-based approach is extensible with respect to the kinds of policies that can be expressed. New policy parameters, such as functional allocations of spectrum, geographic restrictions, temporal restrictions, can be easily defined according to future needs or requirements.

6.3 Field Test Results

DARPA has several mandated metrics for XG network, which are: 1. “must do no harm”, i.e. avoiding interference to primary users; 2. “must work”, i.e. XG nodes are able to form and maintain connected networks; and 3. “must add value”, i.e. spectrum are used efficiently. For each metric, there are several sub-metrics. These sub-metrics include: (1) Channel abandonment time. To avoid interference to primary users, XG nodes should abandon a channel when it detects a non-XG user transmitting on this channel in less than 500 msec; (2) Network join time, which is defined as the time it takes for an XG node to join a pre-existing XG network. The goal is to have XG nodes be able to join existing networks within 5 seconds; (3) Network re-establishment time. When a primary transmitters signal is detected on a channel, XG network should abandons the channel and reestablish network connectivity on a clear frequency within 500 milliseconds; (4) No pre-assigned frequencies is required for XG network startup, i.e. no common control channel; (5) Success in channel use. It is defined as the percentage of time a channel is found when needed.

To test whether XG network meets DARPA’s metrics, field test are designed and carried out in realistic environments. Using the declarative policy engine for spectrum sharing, XG field test was performed for peer-to-peer ad-hoc communication. XG radios used a WiMAX physical layer and operated as either base stations or subscribers following the WiMAX architecture. The transmit power level was 20 dBm. XG Radio uses dynamic spectrum sharing technology to determine locally unused spectrum by sensing radio signals from primary users over a wide spectrum of frequencies (225-600MHz), and then operates on six channels (also within 225-600MHz) without causing interference to the existing primary users. The XG Radios were installed in vans to enable mobile testing.

There are two scenarios in XG network field test. Scenario 1 used three pairs of XG Radios. Each pair was instructed to maintain communications with each other, and to ignore the other XG nodes. Each XG Radio pair was allowed to dynamically select one out of six channels. Scenario 2 used four XG Radios that were instructed to form a radio net using a single 1.75 MHz bandwidth channel. If any of the four XG Radios had to abandon the channel to avoid interference, then all of the radios would rendezvous on a new channel. Scenario 2 is a more difficult problem than Scenario 1 because of the complexity in negotiating for a common channel. In all scenarios there were five pairs of primary DoD and commercial radios operating in the area. Each of these radios used a different channel that overlapped with the six channels that the XG Radio was allowed to use. Primary radios were stationary, while XG radio networks were tested in both stationary and mobile scenarios. From the experiment results, all these criteria are satisfied (graphs of results are omitted for brevity), and especially for Criterion 3, spectrum holes are filled with high factor and channels have high utilization.

6.4 Evaluation

According to the taxonomy descried in Section 2.3.2, and deducing from the descriptions of field test in [11, 20, 28], we infer that spectrum sharing in DARPA XG is a distributed one, where secondary nodes are cooperative with multiple radio interfaces but without using a CCC. We summarize the strengths and limitations of XG radios as following:

Strengths:

- While previously there were intense research activities in dynamic spectrum access networks and a lot of spectrum sharing designs have been proposed, DARPA XG is the first one to demonstrate that dynamic spectrum access network can actually operates in realistic environments and is able to efficiently utilize spectrum resources.
- XG network satisfies all three mandated criteria ("must do no harm", "must work", and "must add value") by DARPA. In current spectrum sharing research, most of them focus on the optimization goals such as minimizing interference, maximizing throughput, etc. DARPA's criteria can serve as metrics for future research.
- Declarative policy engine has the advantage of high-level, independence, flexibility and extensibility compared to traditional imperative radios. Declarative policy engine greatly simplifies the work of engineers when designing spectrum sharing techniques.

Limitations:

- Due to confidentiality, no core algorithm or detailed architecture is mentioned about the spectrum sharing technique used in XG program.
- Though realistic experiments have been carried out in real fields to demonstrate XG radios' capability, these experiments are still relatively preliminary. More complex environments remain to be explored, such as testing a network with more XG nodes (instead of only 6) and more wider spectrum (instead of only 225-600MHz).
- While DARPA's three criteria are effective, other metrics such as throughput, fairness, and latency may as well been set as goals as well [22].
- In current declarative policy engine of XG, only preliminary and straightforward policies (such as "allow" or "disallow" under certain "condition") can be enforced. The policy engine can not deal with more complicated spectrum sharing techniques, e.g. in Section 2.3.1 how to express the graph coloring optimization goals and solve it distributively among secondary users. These interesting problems are good topics for future work.

7 Discussion and Future Direction

7.1 Comparison

In previous sections, we have discussed representative spectrum sharing techniques in DSA networks, including DSAP [7] in Section 3, DOSS [19] in Section 4, HD-MAC [34] in Section 5, and XG [1] in Section 6. These techniques together with formal analysis in Section 2.3.1 show that DSA networks can indeed reduce interference and increase throughput by opportunistically utilizing available spectrum. Problems such as hidden/exposed terminal problems can also be solved by well designed spectrum sharing. Here we evaluate the performance of each of the four spectrum sharing techniques and provide a summary in Table 3.

- Design complexity. DSAP's centralized architecture with CCC and multiple radio interfaces greatly simplify its design, hence making its design complexity the lowest one. HD-MAC and XG have highest design complexity, due to their distributed nature and no use of CCC. DOSS are considered to be in between.

- Range of optimization. DSAP can apply various optimization goals and policies in the DSAP server, which potentially giving it the highest level for range of optimization. DOSS does not consider any optimization goals for spectrum sharing. HD-MAC proposes a novel metric for data channel selection which considers both traffic load and interference level. XG can deal with preliminary and straightforward policies for spectrum sharing. Hence both HD-MAC and XG are considered to have medium range of optimization.

- Scalability. Centralized architecture and the use of CCC significantly limit the scalability of DSA networks, which results the lowest scalability for DSAP, medium for DOSS, and high for HD-MAC and XG.

- Security. Due to the use of CCC, which is vulnerable to security attack such as jamming, the security performance of DSAP and DOSS is not good. However, DSAP can deal with non-compliant (misconfigured and/or malicious) devices, which cause detrimental behaviors to DSA networks by interfering with compliant users. DSAP server can reconfigure compliant clients to minimize negative effects. Hence DSAP is considered to have better security performance than DOSS. Both HD-MAC and XG have high level of security due to the lack of a CCC.

- Device cost. The cost of devices in DSA networks is mainly involved with the number of radio interfaces, when other hardware are roughly similar. Multiple radio interfaces incur higher device cost for DSAP, DOSS and XG than single radio interface for HD-MAC.

- Flexibility. XG declarative policy engine for spectrum sharing is much more flexible than imperative approaches such as DSAP, DOSS and HD-MAC, in that it can potentially express a large variety of policies and also the policies can be dynamically loaded and changed.

7.2 Challenges

Although intense research has been made in DSA spectrum sharing and many designs have been proposed, there are still challenges and many open questions to be solved.

Performance	**DSAP**	**DOSS**	**HD-MAC**	**XG**
Design complexity	Low	Medium	High	High
Range of optimization	High	Low	Medium	Medium
Scalability	Low	Medium	High	High
Security	Medium	Low	High	High
Device cost	Expensive	Expensive	Cheap	Expensive
Flexibility	Low	Low	Low	High

Table 3: A summary of the performance evaluation for different spectrum sharing techniques

1. Channel characteristics include radio range, capacity, interference level, path loss, wireless link errors, link layer delay, holding time, etc. In dynamic spectrum access networks, since a huge portion of the spectrum is potentially usable, it is clear that characteristics of channels may not be constant due to the effects of operating frequency. Differences in channel characteristics will significantly affect spectrum sharing. For example, since radio range varies for different channels, two nodes may be connected under Channel 1 but not under Channel 2. Network interference profile will also change under different channels. Up until now, the challenge of channel heterogeneity is not handled well. For simplification of the spectrum sharing problem, most research papers, including all the ones mentioned in this report, assume that capacity, radio range and bandwidth of all channels are the same. Frequency aware spectrum sharing techniques will definitely increase design complexity and is a good topic for future research.

2. Since spectrum sharing needs the spectrum information reported by spectrum sensing, problems arise if there is inaccuracy or inconsistency in spectrum information. For example, a node may accidentally find that available channel set is $\{A, B, C\}$, while actually there is a primary user using Channel A. Under the wrong available spectrum information, interference may happen. Moreover, since DSA networks could use a huge range of spectrum, the whole spectrum can not be sensed all the time. Additionally, spectrum sensing needs to be suspended during data transmission for single radio interface, spectrum sensing may not be performed on time. Therefore, spectrum sharing should try to deal with spectrum inaccuracy and inconsistency problem in future.

3. There could be non-compliant (malfunctioning and/or malicious) devices which on purpose interfere with compliant users by occupying the same spectrum. It is ironic that the main advantage of the dynamic spectrum access is also its main weakness [23]. Although in DSAP [7] the server will instruct complaint devices to switch to other spectrum when non-compliant devices are detected and in XG the declarative policy engine can enforce various policies to deal with non-compliant devices, a general approach is absent in current research.

4. When primary users begin to occupy some spectrum, affected secondary

users have to switch spectrum. This spectrum mobility may incur transmission delay and packet loss, etc. However, it should be transparent and as soon as possible such that users experience minimum performance degradation [4]. For example, FTP traffic needs to be buffered during spectrum switching, but not for real-time traffic. Most recent papers assume that spectrum mobility take no time, which is obviously not true in practice.

5. In Figure 4 we mentioned that spectrum sharing could involve with the network layer. It is advantageous to consider cross-layered spectrum sharing. The simulation results in [31, 32] reveal that a cross-layer spectrum sharing design that constructs routes and determines the operating spectrum jointly for each hop outperforms the approach where routes are selected independently. In DSA networks with multi-hop communication requirements, novel routing algorithms are necessary but are also full of challenge, as well as other upper layers. Spectrum sharing which considers upper layer issues such as routing, flow control and congestion control remains not-so-well exploited. In the papers we surveyed, none of them consider upper layer issues for spectrum sharing.

6. Up until now, most research efforts have been focused on simulation only (maybe due to the difficulty of performing emulation for DSA networks), and only preliminary realistic experiments are carried out to test the performance of DSA spectrum sharing, such as DARPA XG program. More realistic experiments are needed for the development of DSA networks in future.

7. Current declarative policy engine of XG can only deal with preliminary and straightforward policies (e.g. allow/disallow). The policy engine can not handle more complicated spectrum sharing techniques, e.g. in Section 2.3.1 how to express the graph coloring scheme and solve it either centralizedly or distributively. It is an interesting topic for future research about how to make declarative policy engine able to deal with complicated spectrum sharing policies.

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A Multi-channel 802.11 MAC

There have been extensive studies on assigning interfaces to channels (or vice versa) in multi-channel wireless networks with each node having one or more radio interface(s) [11, 29], mostly designed for IEEE 802.11 and similar networks [32]. Although these studies in multiple-channel 802.11 MAC share some similarity with DSA in that they both allow opportunistic access to different parts of spectrum due to changing environments, these algorithms are not suitable for DSA networks due to following reasons [32].

1. The spectrum used for opportunistic sharing in multi-channel 802.11 MAC is insignificant compared to the entire spectrum that is suitable for wireless communications in DSA. With more spectrum opened up for opportunistic

sharing, DSA can take full advantage of the more technically attractive wideband spread spectrum technologies, such as Ultra Wide Band (UWB) and CDMA.

2. In multi-channel 802.11 MAC, the channels are static and all channels are available for every node, and thus nodes can freely switch interface to any channel for communication. This is not true for DSA. In DSA networks, secondary nodes can only access the spectrum which is currently unused by primary users and often is a very small subset of the whole spectrum. Furthermore, different secondary users may sense different available spectrum due to geographic heterogeneity or presence of different primary users, etc.

3. DSA networks are very different in nature from 802.11 networks, where all channels are in the 2.4 GHz or 5 GHz ISA band. In DSA networks, the channels are distributed across a large spectrum and two channels may be separated with a large band being used by primary users. Different spectra in DSA networks show significant channel heterogeneity (capacity, bandwidth, transmission range, etc) compared to 802.11 channels.

4. Multi-channel algorithms break up a certain spectrum band into a number of fixed channels, which may result in low spectrum utilization because of the notion of unbreakable channel quantum. Second, a channel is considered busy even if a small fraction of it is being occupied (by legacy spectrum users or hostile interferences). Therefore, for efficient spectrum utilization, nodes should be flexible in selecting the spectrum so as to take full advantage of all spectrum opportunities, such as in DSA networks.

B Radio spectrum allocation in United States

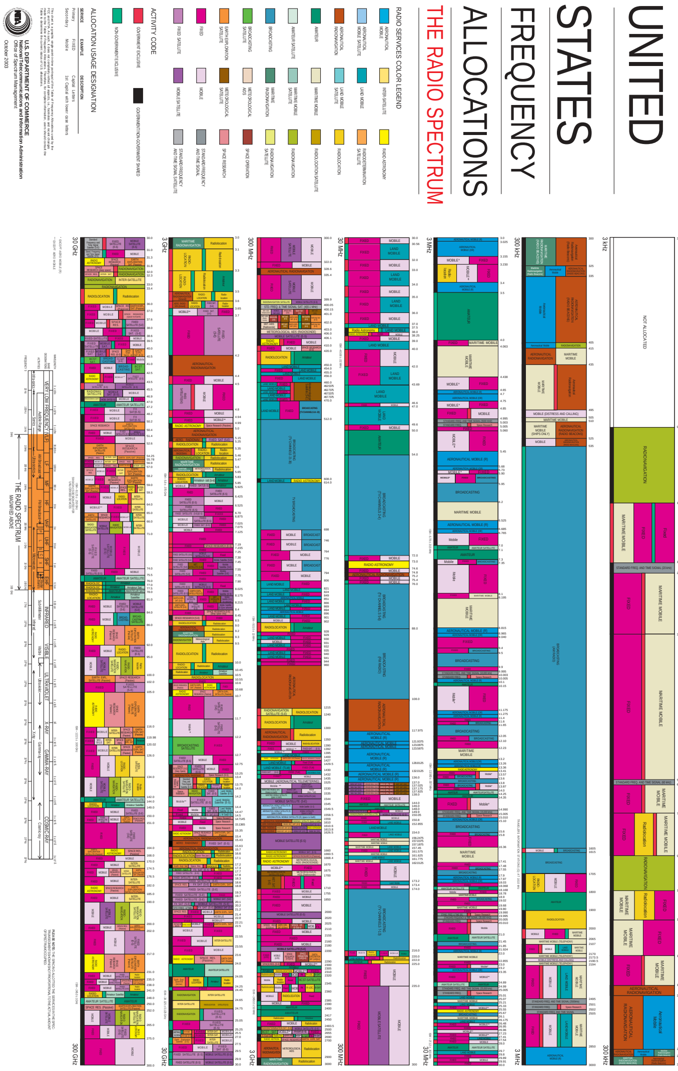

Figure 14: Radio spectrum (3KHz - 300GHz) allocation in United States