Abstract—Dynamic spectrum access (DSA) technique enables dynamic access of unused or under-utilized spectrum without causing interference to existing incumbent service. Through DSA, a DSA device (second user) is offered opportunities to monitor a swath of spectrum, which is divided into myriad channels, in the licensed band. A great number of available channels offers DSA networks higher throughput as a whole and allows DSA MAC design to adopt frequency domain backoff scheme to avoid unnecessary delay in particular. Our observation indicates that the operation range (OR), the set of available channels that the MAC of a DSA device would use, has significant impact on the throughput performance of the MAC that adopts frequency domain backoff scheme. Three OR strategies, namely non-sharing (NS), partial sharing (PS), and full sharing (FS), are thoroughly studied. To validate our design, a slotted CSMA model with poisson packet arrival rate is developed to analyze the performance of the three OR strategies. We also conducted simulations to verify our theoretical work. We found that there is tradeoff between the throughput and the white space filling rate. While FS gives the best throughput performance, NS has the best performance in terms of white space filling rate.

I. INTRODUCTION

A feasible solution to the problem of spectrum scarcity [1] is to allow the unlicensed spectrum service (secondary service) to exploit the white space in the licensed spectrum and restrain the interference to the licensed users under an acceptable level. This technology is referred as dynamic spectrum access (DSA) which is closely related to the cognitive radio (CR) or spectrum agile techniques [2]–[5].

A DSA device monitors a swath of spectrum including those occupied by the licensed services and tries to identify the “white space” (spectrum hole), which is the idle period in between consecutive accesses of licensed users. Then, it exploits such transmission opportunities in the specific locality to communicate with neighboring DSA nodes. According to the latest XG field test [6], a DSA device must do no harm to the incumbent service, while its medium access control protocol has to utilize the opportunity efficiently by keeping the white space filling rate high. Therefore, the design of DSA MAC is one of the most challenging works in developing DSA networks. A MAC protocol is responsible to resolve collisions on the selected channels. For a DSA network, collisions could happen when the primary and the secondary services or multiple DSA transmissions select the same channel with overlapped time. The set of channels a DSA node would listen to and attempt to utilize is its operation range (OR). Also, a great number of available channels allows a DSA MAC design to adopt frequency domain backoff scheme to avoid unnecessary delay. Then, the way of assigning OR to a DSA node becomes a crucial issue, as it will be shown in this paper that OR assignment does affect the performance of such DSA MAC design. Therefore, in this paper, we propose a DSA MAC which adopts frequency domain backoff scheme and explore the impact of different OR strategies on the throughput performance and white space filling rates through theoretical analysis and simulation.

The rest of the paper is organized as follows. Previous work on DSA MAC is reviewed in Section II. Then, the proposed DSA MAC is presented in Section III. In Section IV, we developed the theoretical model to analyze the performance metrics of three OR strategies. Simulation results are given in Section V to validate our analytical model. Finally, concluding remarks are drawn in Section VI.
channel availability; second, a performance metric function that defines the strategies; third, an approach to make a decision on selecting a channel to sense and access. The optimal DC-MAC was optimized based on Partially Observable Markov Decision Process (POMDP), and the lower complexity suboptimal version is given based on a greedy approach. The decision on channel selection is made based on slotted time assumption.

A dual-band statistical channel allocation MAC (SCA-MAC) [10] is proposed to address the interoperability concern and achieve higher efficiency of spectrum utilization by predicting spectrum hole (white space) based on history. SCA-MAC allows DSA devices to do real-time opportunistic access on any continuous part of the spectrum, licensed or not. Furthermore, the SCA-MAC device gains extra intelligence by sensing the environment and collecting the spectrum usage statistics. Based on the statistics, the probability of successful transmission and the chance of interference to licensed users could be evaluated through a theoretical model. The interference-free control channel is also employed in [11]. Unlike SCA-MAC that predicts future spectrum holes based on channel access history, it uses Bayes’ theorem to predict the future available channels.

A Philips sponsored work [12] propose a prototyped cognitive MAC, called C-MAC, for multi-channel wireless networks. C-MAC is a time-slotted protocol in that each channel is divided into recurring superframes which, in turn, include a slotted beaconing period (BP) where nodes exchange information and negotiate channel usage. C-MAC employs a rendezvous channel (RC) for coordination amongst nodes in different channels. A backup channel (BC) is also introduced and is employed to provide a choice of alternative channel as RC in case of the appearance of an incumbent. This makes the RC more robust to incumbents. Another time-slotted protocol is proposed in [13], where synchronous operation is proposed, i.e. time is slotted in each channel. It also assumed that a MAC controls two transceivers, one is dedicated to control channel and the other is used to CR sensing and data transmission over data channels. The same authors of [13] also propose a CR based multi-channel MAC protocol for DSA networks in [14]. This new design uses only one transceiver but is with multiple channel sensors. Using two-way handshakes of control packets, this protocol enables the secondary users to opportunistically utilize the unused frequency spectrum while avoiding the collisions among secondary users and the collisions between secondary and primary users.

In [15], a CR MAC, called COMAC, is proposed. COMAC does not assume a predefined CR to primary user (PU) power mask and does not require active coordination with PUs. In this work, probabilistic models are developed for the PU-to-PU and the PU-to-CR interference under a Rayleigh fading channel model. From these models, closed form expressions are derived for the mean and variance of interference. Based on the developed interference models, the authors derive a closed-form expression for the maximum allowable power for a CR transmission that ensure a statistical bound for PUs. However, a CR network may operate over a wide range of channels, and a power mask is often enforced on the transmission of a CR user to avoid corrupting the transmissions of PUs. To avoid unnecessary blocking of CR transmissions, the same authors also propose a distance-dependent MAC, called DDMAC, in [16]. In order to maximize the CR network throughput, DDMAC uses a probabilistic channel assignment mechanism that exploits the dependence between the signals attenuation model and the transmission distance while considering the traffic profile. This way, it allows a pair of CR users to communicate on a channel that may not be optimal from one users perspective, but that allows more concurrent transmissions to take place, especially under moderate and high traffic loads.

The performance of different multi-channel MACs is thoroughly compared and analyzed in the context of opportunistic spectrum access in [17]. These MACs designed for multichannel CR networks all adopt the time domain backoff scheme to reduce collisions. In summary, the fact that the multiple available channels in CR environment allows a DSA MAC designer to adopt the frequency domain backoff scheme has been neglected. In this paper, we thus propose a multi-channel DSA MAC that uses the frequency domain backoff scheme and investigate how different ways of OR selection affect the throughput performance.

III. PROPOSED DSA MAC PROTOCOL

Although there may be quite a few nodes within a DSA network, a transmission could only be interfered by a node’s neighboring nodes. In our model, we define a node and its neighboring nodes as a network unit. When there is an ongoing transmission between the node and one of its neighbors, no other neighboring nodes could transmit on the same channel. In other words, a node and its neighbors share the local frequency resource. A large scale wireless network is cascaded by some of such basic units. In our model, we ignore the boundary nodes of the DSA network. Since a DSA system exploits locally unused frequency resource, it generally requires much wider spectrum to secure sufficient transmission opportunity. Therefore, a DSA wireless networks is always a multichannel system. The number of channels a node could use, which is defined as the operation range (OR) of a node, could be larger than the number of neighboring nodes it has. In this work, we assume all the channels are slotted, as illustrated in Fig. 1. In the figure, a white slot indicates that the slot is not used by either primary service or the DSA nodes, so the slot is idle. A gray slot means that only one pair of DSA nodes access the slot and the transmission is successful. A dark slot represents a collision. A collision (or an interference) happens when two or more neighboring nodes’ transmission overlapped in time and in frequency. The collision resolution mechanism of the DSA MAC is responsible for reducing the collision rate.

Spectrum sensing is crucial to the success of DSA networks. Through continuous sensing, a DSA node learns about the environment and then adapts to it. The adaptation is via its MAC. Therefore, a node’s MAC is responsible for avoiding
interfering primary service and establishing link between neighboring nodes. For example, if a node sensed that primary service is extremely busy on a certain channel, the node’s MAC is responsible to exclude the channel from its operation range. Assigning channels exclusively could avoid collision among neighbors, but it also means less opportunity to exploit the white space.

In addition to reducing collision through OR assignment, a DSA MAC should also resolve collision efficiently after it happens. There are two kinds of collisions, collision with the primary service or with another DSA transmission. Upon a packet arrival, a DSA randomly picks a channel from its operation range and then begins listening to the channel. During this period, a DSA node should be intelligent enough to recognize any ongoing incumbent service. Since all DSA communications should do no harm to the primary service, a DSA node quits listening to the channel once it detects any ongoing primary service. Then the DSA node would try to transmit again on the next time slot. Although there is no lost packet in this scenario, we still call this kind of incidents as primary service collisions. If the DSA node decides that the channel is free of primary service, it then begins its transmission. In our slotted model, a primary service always occupies the whole time slot. However, other neighboring nodes may also select the same channel to transmit. This kind of incidents is called DSA collision. Then each node will select a channel from its OR again and try to retransmit on the next time slot.

Upon a collision, traditional time domain resolution postpones the transmissions randomly to later time slots on the same channel, which is scenario (1) of Fig.1. Since the DSA system has multiple channels, we propose a collision resolution scheme that adopts frequency domain backoff scheme which exploits the nature of multiple channels for resolving contention and also decreases the possible delay. The frequency domain backoff scheme retransmits in the following slot like the 1-persistent ALOHA, except instead of sticking to the same channel, it randomly selects one of the channels within the node’s OR. Therefore, the randomness is done in the frequency domain, referring to scenario (2) of Fig.1. Compared to backoff in time domain, backoff in frequency domain produces less delay, and thus it is also referred as fast retrial algorithm [18], [19] in the OFDMA networks. Although aforementioned two kinds of collisions are fundamentally different, they are both resolved by the same frequency domain backoff scheme.

IV. ANALYSIS OF OPERATION RANGE ALLOCATION STRATEGIES

The set of channels that a node would use is called the operation range (OR). The OR of any node is a subset of total available channels. Typically, OR is managed by the DSA MAC. In this section, we analyze three OR strategies: non-sharing scheme, partial sharing scheme, and full sharing scheme. In fact, the non-sharing scheme and the full sharing scheme are special cases of the partial sharing scheme. By comparing the performance of these three schemes, we gain insights perspectively.

We established an ALOHA-like model to do the theoretical analysis. The Poisson distributed packet arrival rate of each DSA node is represented as $G_i$ and the arrival rate of primary service on each channel is $G_p$. There are totally $M$ available channels and each node has the same number of neighboring nodes, which is represented as $n$. The size of OR of a DSA node is $m$. Let $G_t$ denote the total packet arrival rate on a channel, which includes packets from both primary and secondary service. We then calculate the important performance metrics. The major metrics we used to evaluate these strategies are throughput and white space filling rate. First, the throughput, represented as $S$, of a node is the product of its packet arrival rate and the probability that the medium is idle for a time slot. Therefore, it is expressed as

$$S = G_t e^{-G_t}. \quad (1)$$

For a time slot, the chance that it is not occupied by the primary service is $e^{-G_p}$. Similarly, the chance that it is not used by any service is $e^{-G_t}$. Since the white space is defined as time slots not used by the primary service, the white space filling factor, represented as $W$, is defined as the probability that a white space is occupied by a secondary transmission. For a channel, the white space filling rate is expressed as

$$W = 1 - \frac{e^{-G_t}}{e^{-G_p}}. \quad (2)$$

With Eqs. 1 and 2, to evaluate the performance metrics, the job left to do is to find the total packet arrival rate of each OR strategy.

A. Non-sharing OR strategy (NS)

The non-sharing OR strategy is to allocate a part of the spectrum exclusively to a node. By using this strategy, a node could avoid collisions caused by another DSA node since there will be no transmission overlapped in frequency even if there is overlap in time. Although non-sharing OR strategy eliminates collisions among DSA users, the OR size of a node

Fig. 1: Slotted multichannel model of the DSA system.
also shrinks by several fold, which means lower transmission opportunities for a DSA node.

For a channel, the total packet arrival rate, $G_t$, of a time slot $i$ must consider the new arrival packets and the retransmissions due to collisions at the previous time slot $i-1$. At any time slot, if the arrival rate of new packets is $G_0$, then

$$G_t(i) = G_0 + P_c P_m G_t(i-1),$$

(3)

where $P_c$ is the probability of collision at the previous time slot $(i-1)$, $P_m$ is the probability that the node would pick the same channel to transmit again at this time slot, i.e., slot $i$. In a steady state, we could express $G_t$ as

$$G_t = \frac{G_0}{1 - P_c P_m}.$$  

(4)

For non-sharing strategy, MAC distributes the local frequency resource equally to neighboring nodes, thus, the size of OR is $m = \frac{M}{n}$. The arrival rate of new packet of a non-sharing node is

$$G_{ns}^n = G_p + \frac{G_t}{m}. $$

(5)

We could further calculate

$$P_c = (1 - e^{-G_p})(1 - e^{-\frac{G_t}{m}}) \text{ and } P_m = \frac{1}{m}.$$  

For non-sharing case, since there is no collision among secondary service, the collision only due to primary service. Then finally the total arrival rate of non-sharing $G_{ns}^n = G_{ns}$ could be found through Eq. 4. Then, the throughput of the non-sharing scenarios could be expressed as

$$S_{ns} = G_p e^{-G_{ns}},$$

(6)

and the white space filling factor is expressed as

$$W_{ns} = 1 - e^{-G_{ns}}/e^{-G_p}.$$  

(7)

B. Full sharing OR strategy (FS)

Using full sharing strategy, each DSA node fully shares the local frequency resource with neighboring nodes and thus the size of OR is $m = M$. Since the traffic of all nodes is distributed to $M$ channels, the arrival rate of new packet on a channel becomes

$$G_{fs}^0 = G_p + n \frac{G_t}{M}. $$

(8)

There is possibility that a transmission may be interfered by neighboring nodes. The collision probability includes not only the backoff incurred by primary service but also the transmission collisions among neighboring DSA nodes. Thus, $P_c$ becomes

$$P_c = (1 - e^{-G_p})(1 - e^{-\frac{G_t}{M}}) + e^{-G_p}(1 - e^{-\frac{n G_t}{M}} (1 + n \frac{G_t}{M})).$$

(9)

The first term of Eq. 9 is the probability of collision in the previous time slot due to primary service, and the second term of Eq. 9 is the probability of collision caused by mutual interference among neighboring nodes. Along with $P_m = \frac{1}{M}$, we could calculate $G_{fs}^n = G_{fs}$ from Eq.4. Then, we could express the throughput of the full sharing scenario $S_{fs}$ as

$$S_{fs} = G_p e^{-G_{fs}}.$$  

(10)

In a similar fashion, the probability of slot collision is expressed as

$$Q_{fs} = 1 - (1 + G_{fs}) e^{-G_{fs}},$$

(11)

and the white space filling factor is expressed as

$$W_{fs} = 1 - \frac{e^{-G_{fs}}}{e^{-G_p}}.$$  

(12)

C. Partial sharing OR strategy (PS)

The partial sharing strategy allows a node to control how much it want to share its OR with neighbors. Generally, the size of the partial sharing OR of a node is between $\frac{M}{n}$ (non-sharing) and $M$ (full sharing). Under the partial sharing OR, a channel may be reused by some of the neighbors. We use $r$ to depict the reuse degree of a channel. Unlike the fixed $r$ of the previous two strategies\(^2\), the reuse factor may be different from a channel to another in partial sharing scenario. However, through a simple trimming algorithm, we could average the reuse factor of each channel and reduce it to the theoretical upper-bound with respect to its OR size, which is $\lceil \frac{n m}{M} \rceil$. Then, we calculate in average how many neighbors a DSA node shares a channel with, which is expressed as

$$n' = (r-1) + \frac{b}{M},$$

(13)

where $b$ is the remainder of $n \times m$ dividing by $M$.

Since a channel is shared by $n'$ nodes in average, the arrival rate of new packet on a channel becomes

$$G_{0ps}^n = G_p + n' \frac{G_t}{m}.$$  

(14)

With $P_c$ equals to

$$P_c = (1 - e^{-G_p})(1 - e^{-\frac{n' G_t}{m}}) + e^{-G_p}(1 - e^{-\frac{n' G_t}{m}} (1 + n' \frac{G_t}{m})).$$

(15)

Similar to Eq.9, the first term is due to primary service and the second term accounts for the collision among secondary service nodes. With $P_m = \frac{1}{M}$, we could find $G_{ps}$

$$G_{ps} = G_{fs}^n = \frac{G_{0ps}^n}{1 - P_c P_m}. $$

(16)

The performance metrics are calculated in a similar fashion. The throughput of partial sharing scenario is

$$S_{ps} = G_p e^{-G_{ps}},$$

(17)

and the slot collision probability could be found as

$$Q_{ps} = 1 - (1 + G_{ps}) e^{-G_{ps}},$$

(18)

\(^2\)For any channel, $r = 0$ for non-sharing strategy and $r = n$ for full sharing strategy.
and the white space filling factor is expressed as

$$W_{ps} = 1 - e^{-G_{ps}/G_p}.$$  \hspace{1cm}(19)$$

Observing the equations of three strategies, we could assign proper value to \(n'\) and \(m\) to obtain the equation of the other two strategies. Thus, we concluded that full sharing and non-sharing are just two extremes of the partial sharing strategy. Although the number of neighboring node is fixed in the above analytical model, the model could be extended to consider the case when the number of neighboring node is a variable, \(n_i\). If the average and variance of the distribution are known, it is not hard to find the average throughput and white space filling rate.

V. SIMULATIONS

In our simulation, the channel is slotted and we assume a primary service with poisson distributed arrival rate of \(G_p\) on each channel. The packet arrival rate of a DSA node is also poisson distributed. When a DSA node wants to access a channel, it first listens to the channel for a short period of time to decide whether there is a ongoing primary service. If there is one, it randomly picks another channel from OR and tries again at the next time slot. If the channel is clear, it begins its transmission. The channel abandonment due to discovered primary service protects the primary service from being interfered by collocated DSA nodes. Nevertheless, packet losses are still possible due to collisions among DSA nodes. Since the number of available channels is generally larger than the number of neighboring nodes, we did not implement any random backoff procedure before the DSA transmission, only frequency domain backoff is implemented to resolve the collisions among DSA nodes afterward. The frequency domain backoff of our DSA MAC behaves like 1-persistence ALOHA. It retransmits again at the next time slot, except likely on a different channel. All the channels of OR have equal chance to be chosen in each transmission trial.

Four cases, namely full sharing, non-sharing, and two different degrees of partial sharing, are simulated in each scenario. When a strategy is chosen, all DSA nodes adopt the same strategy. We ran the simulation for 1000 time slots for a single trial and each plotted value on the figure is the average of at least 20 trials. Since simulation results match those predicted by the theoretical model, we only show the simulation results in the figures.

A. Throughput of different OR strategies

This set of simulations aims to show the throughput under different traffic load of the primary service and then different load on the DSA nodes.

Fig. 2 shows the throughput performance of different strategies with fixed arrival rate of each DSA node. The rising arrival rate of the primary service increases the burden on each channel which implies less white space for the secondary service. When the traffic load of the primary service is moderate, the performance gap between different strategies is obvious. However, as the traffic load aggravates, the gap shrinks accordingly. Fig. 3 shows the throughput performance of different strategies with fixed primary service arrival rate. The impact of the OR strategies is obvious for this scenario and full sharing really has the edge over non-sharing. The throughput topped at some arrival rate, which is the optimal operation traffic load for a DSA node under the effects of multiple parameter, \(i.e.\) channel number, neighboring node number, and primary service arrival rate. Thus, the ideal traffic load is expected to shift right when primary service arrival rate decreases and vice versa.

B. White space filling factor of different OR strategies

Figs. 4 and 5 show the white space filling factor of different OR strategies. Unlike throughput, non-sharing strategy performs the best in this category. With smaller OR and therefore less channel to operate on, non-sharing strategy has less flexibility but to focus on filling the white space on its
strategy provides the best performance on throughput but the verify our finding. Simulation results show that full sharing and partial sharing. Simulation was conducted to develop a theoretical model to explain the performance difference between three OR strategies, namely, non-sharing, full sharing, and partial sharing. Simulation was conducted to verify our finding. Simulation results show that full sharing strategy provides the best performance on throughput but the worst performance on white space filling rate. Therefore, there is a design issue on the tradeoff between throughput and white space filling rate. The decision on operation range of a node depends on the requirements on those performance metrics. In this paper, we did not consider the overhead due to the channel switching, channel selection, and operation range selection. In the future work, we plan to collect more realistic statistics and include those overheads in our analytic model and simulation. This paper provides insights on how to handle tradeoff between throughput and white space filling factor in the design of DSA MACs for cognitive radio networks.

VI. CONCLUSIONS

In this paper, we proposed a DSA MAC for multi-channel wireless ad-hoc networks, which is capable of adapting operation range and resolving collision through frequency domain randomness. The contribution of our work was using the frequency domain backoff scheme in the design of DSA MAC and studied the impact of operation range selection on the performance of throughput and white space filling rate. We developed a theoretical model to explain the performance difference between three OR strategies, namely, non-sharing, full sharing, and partial sharing. Simulation was conducted to verify our finding. Simulation results show that full sharing strategy provides the best performance on throughput but the

OR. These two figures also implies the primary service traffic load has much more impact on the performance of white space filling than the arrival rate of DSA nodes.

REFERENCES