

Discrete OFDM-Based Channel Assignment Scheme for Agile Networks

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Abstract: The main goals of all new technologies nowadays are utilizing the available spectrum, increasing spectrum efficiency, and increasing the throughput. Cognitive radio (CR) technology can provide efficient spectrum utilization and maximize the throughput using dynamic spectrum access technique. A new medium access control (MAC) protocol is needed for CR users to access the spectrum dynamically and to maintain fairness between users. In this paper, our objective is to enhance the overall network throughput, by enhancing SMART-V MAC protocol to support D-OFDM technology. A new channel assignment scheme called SMART-O based on these two technologies is proposed. The proposed algorithm greatly increased the overall throughput of the network and solved the channel assignment and rate optimization problems. Simulation results exposed the improvement of our work compared to previous algorithms.

Keywords: Cognitive radio (CR), MAC protocol, D-OFDM, SMART V, channel assignment.

1. Introduction

Cognitive radio (CR) is a new technology that exploits the unused spectrum bands. The user that uses licensed bands called primary user (PU). The studies from Federal Communication Commission (FCC) and other organizations show that the utilization of the licensed spectrum, ranging from 15% to 85% [1]. CR introduces secondary user (SU) that exploits these licensed opportunistically by reconfiguring its own operating parameters to establish its communication without interfering the PU. There are two types of bands that the CR can exploit: The unused bands, which called white holes, and the partially used band by the PU, which are called Gray holes. In gray bands, the SU can operate with the existence of the PU but appears as interference and should not exceed specific threshold. Because of that the spectrum utilization and over all throughput are improved.

There are four main functions of cognitive radio network (CRN), spectrum sensing, spectrum management, spectrum sharing and spectrum mobility.

CR users can access any portion of spectrum opportunistically using dynamic spectrum access (DSA) mechanism. Such a mechanism needs a good MAC protocol design.

In this paper, we deal with overlay spectrum management with the objective of optimizing the spectrum utilization by using the technology of D-OFDM. We also represent the new algorithm that achieves the maximum sum-rate performance of all CR transmissions better than OPT-MAC, which called SMART-V technology. Our objective is to merge these two technologies (SMART-V and D-OFDM) and study the effect on the overall throughput. We also consider the case where each transmitter has multiple packets to many users.

A. Motivation and Contribution

Several previous attempts were based on multiple transceivers CR nodes to maximize the throughput of the cognitive radio network (CRN) which is unrealistic due to the hardware complexity and high cost. It is worth mentioning that the term agile networks is used to describe CRNs that can be dynamically and opportunistically utilize the available spectrum bands by changing their operating RF environment.

The communication technologies are rapidly developed in large scale, and new good technologies were emerged like discontiguous-OFDM (D-OFDM) that enable for increasing network throughput by dividing the available channels into sub-channels. Some attempts were made to have the CRN and the Primary Radio Network (PRN) cooperate while the CRN should operate separately from PRN and other attempts assumed that each node must have multi-

transceivers. This leads to hardware complexity. However, a new channel assignment scheme is proposed in literature (i.e. SMART-V) which is an enhancement scheme for OPT-MAC technique that enhances network throughput by maximizing the sum-rate of all contending CR nodes and greatly increases the number of data packets that are transmitted in the time-frequency unit. In this work we aim at merging these two technologies (SMART-V technology and D-OFDM technology) into a simple channel assignment scheme, re-state the problem and its formulation, study the system performance, and add some new features to enhance system efficiency. We investigate the channel access problem under transmission power, spectrum opportunities, data size, interference, received SINR, hardware constraints and the effect of using D-OFDM on the overall throughput and spectrum efficiency.

Our objective is to enhance the overall network throughput, by enhancing SMART-V MAC protocol to support D-OFDM technology. SMART-V allows nodes to exploit the available channel in residual time-frequency blocks, while the D-OFDM technology allows several packets to be transmitted to several users from the same node simultaneously. A new channel assignment scheme based on these two technologies is proposed. In other words, our channel assignment scheme allows transmitting a single packet to a single user or transmitting multipackets to multiple users, and other users can exploit the residual time frequency blocks to transmit other packets (or segments of the packet). This scheme based on access window (AW) to collect control information.

B. Related Work

CR is a new technology that benefits from the spectrum holes (or white holes) in the frequency bands and accesses them dynamically; this leads to improve the spectrum utilization and throughput [2-9]. The main issue here is to design a MAC protocol such that it can access the spectrum dynamically. In [2], the authors discussed characteristics of multi-hop CR networks and how to design opportunistic MAC protocol while limiting the interference on the PR.

POWMAC is a distance dependent transmission power MAC protocol [3]. POWMAC increases the spectrum efficiency by controlling the transmission power of the CR user depending on their distance by using transmission power control (TPC). This leads to maximize the network throughput, increase the number transmission and at the same time keep the collision avoidance between the CR nodes.

MRMC-CRNs protocol minimizes the interference to the primary nodes and the interference between the CRNs. In addition, this protocol maximizes the connectivity between the CRNs. Each CR node is equipped with two radio interfaces. The performance is improved but at the expense of hardware complexity and cost [4].

A distributed channel assignment scheme for CR network is proposed in [5]. This scheme reduces the interruption of the CR users' transmission case by vacation from the licensed band after the primary user uses its spectrum. This scheme is called robust interference minimizing channel assignment (RIMCA) scheme and it considers multi-radio multi-channel node architecture. The disadvantage of this scheme is the hardware complexity because each node is equipped with multi transceivers.

Spectrum sensing can be done using many methods. One of these methods is the energy detection method. The advantages of energy detection method are the low complexity and the receiver does not require having prior information of the received signals.

In [6], an offset modulation OFDM (OM-OFDM) is proposed for energy detection spectrum sensing technique under Rayleigh multipath fading channel. This scheme is implemented for digital video broadcasting – second terrestrial (DVB-T2). OM-OFDM deals with constellations that contain both real and imaginary components. This scheme improved the BER and it is shown that it can operate at 15 dB lower SNR than a typical OFDM transmission.

The authors in [7] used non-contiguous OFDM which used to deactivate the subcarriers utilized by PR user and that's leads to interference between PR user and the CR user.

OPT-MAC [10] is a new channel assignment protocol that maximizes the sum rate for all contending cognitive radio nodes and that's leads to maximize the overall throughput of the CR network.

The authors in [11] proposed a centralized CRN based on relay-assisted discontiguous OFDM (D-OFDM) data transmission. Relay nodes are CR users use a portion of the spectrum that they have due to low traffic then they help other CR users with their remaining unused spectrum.

In [12], the authors show the advantages of using OFDM on CR network. OFDM reduces the dispersion effect that results from multipath channel encountered with high data rates. OFDM also provides high spectral efficiency and reduce inter-carrier interference (ICI) by using orthogonal overlapping carriers (subcarriers).

SMART-F MAC and SMART-V MAC are enhancements for OPT-MAC channel assignment scheme [12]. In OPT-MAC, after the admission window phase, the transmission phase will start. This phase will end after the node that has the lowest rate end its transmission and the nodes with higher rates will wait after transmitting their packets.

The aim in [13] is to exploit the residual time frequency blocks to transmit additional packets. SMART-F (Fixed packet length) MAC allows to retransmit the full packet that has been transmitted again. SMART-V (Variable packet length) MAC allows to retransmit the packet or its segments depending on the remaining time for the transmission phase to end.

In this section, a brief overview of previous technologies related to our proposed scheme is provided. OPT-MAC, SMART-V and D-OFDM technologies will be presented here.

1. OPT-MAC

Greedy channel assignment scheme algorithm is simply that each CR node will use the best idle channel available (the channel that has the highest data rate) [14]. To increase the throughput of the system, a cooperative algorithm is used. OPT-MAC channel assignment scheme is a cooperative algorithm that maximizes the sum rate for all contending cognitive radio nodes and that's leads to maximize the overall throughput of the CR network [15]. CR nodes will assign the available channels after they negotiate using the admission window phase.

2. SMART-V

SMART-V MAC protocol is an enhancement to OPT-MAC channel assignment scheme. In OPT-MAC when the transmission starts, it will end after the node that will have the slowest rate finishes its transmission. The nodes with higher rate will wait until transmission phase ends to send other packets. This waiting time is called residual time. SMART-V MAC protocol exploits this residual time and makes the node with higher data rate to resend the packet itself or its segments depending on this residual time. These segments have a packet size $S = \left\{\frac{D}{2^0}, \frac{D}{2^1}, \frac{D}{2^2}\right\}$, where D is the size of the full packet. In other word, for a certain time-frequency block, the first stage is to see if the full packet could be sent. If not, half of the packet will be send and if half of the packet is larger than the residual time, the quarter of the packet is sent [13].

3. D-OFDM

OFDM technology is a multicarrier transmission, where a single data stream could be transmitted over lower data rate channels [6]. It utilizes the spectrum by saving 50% of the bandwidth because of the orthogonality between sub-carriers and reduces the narrow band interference. In D-OFDM, data transmission can be carried over several channels (that are adjacent or not) with the same adjacent subcarriers number. This can be accomplished using a power control on the power of each subcarrier of each channel. The power level of the desired subcarrier will set

to a non-zero value while the power level of the undesired subcarriers will set to zero. This technique made D-OFDM very suitable for CRNs since in such networks availability of the channels is varying according to PRNs activities [8].

C. Organization

This paper has four sections: The network model is presented in section 2. Section 3 introduces the problem formulation and the proposed algorithm. The proposed channel access mechanism is presented in section 4. Section 5 shows the analysis and simulation results and the performance evaluation. Finally, section 6 presents the conclusions and future works.

2. Network Model

Our network model assumption is that the CRN operates with the existence of (PRN) in a finite area, where the PRNs operates over different licensed frequency bands, each with the same bandwidth. Each CR node is equipped with D-OFDM transceiver, which has the ability of utilizing any number of idle spectrum bands. For the purposes of protecting the primary users, the spectrum sensing will provide all the needed information.

For a given CRN, let

C = Idle channels.

T = Total number of transmission requests

L = Total number of available links.

A successful transmission $j \in T$ over an idle channel $i \in C$ via the link $l \in L$, will accure if the $SINR_{j,l}^{(i)}$ at the receiver is greater than some given threshold SINR value (μ^*) to achieve a bit error rate greater than some acceptable BER threshold over channel i.

Let $R_{j,l}^{(i)}$ denotes the rate of transmission (*j*) over channel (*i*) via link (*l*), which is a function of $SINR_{i,l}^{(i)}$, i.e.:

$$R_{j,k}^{(i)} = \begin{cases} f(SINR)_{j,k}^{(i)} &, \text{ if } SINR_{j,k}^{(i)} > \mu^* \\ 0 &, & \text{ otherwise} \end{cases}$$
(1)

3. Problem Statement and Algorithm Description

In this section, we discuss the problem statement and design constraints, and the problem formulation. We also describe our proposed channel assignment schemes, and show how they exploited the residual time-frequency holes effectively and utilize the spectrum efficiently.

A. Problem Statement and Design Constraints

Given the network model, the problem statement can be described as follows:

Given a group of CR users within the same network, they are opportunistically contending to utilize the available spectrum (white holes). The main goal is to maximize the throughput by maximizing the sum-rate achieved by all contending CR users, subjected to the following design constraints:

- 1) Hardware constraints: every CR node is equipped with just one single half duplex transceiver.
- 2) Maximum transmission power: every CR node has a limited transmission power that can transmit over a channel. This power is limited by FCC regulations.
- 3) SINR must be above a specific threshold.
- 4) Exclusive channel occupancy: The occupied channel cannot be allocated for other CR users.

Our MAC protocol follows a multistage optimization technique to increase spectral efficiency, where the needed information for optimization can be extracted from RTS/CTS control packets exchanges.

B. Problem Formulation

Our goal is to maximize the sum rate of all CR transmissions over all channels where each transmitter could access an aggregated channel. Thus, we need to find out the optimal rate and channel assignment.

We define the new binary variable $(x_i^{(i)})$ as follows:

$$x_{j}^{(i)} = \begin{cases} 1, if \ channel \ (i \) \ is \ assigned \ to \ transmission \ (j \) \\ 0, \qquad otherwise \end{cases}$$
(2)

The maximum sum-rate of all contending CR transmission requests with hardware and power constraints can be formulated as [10]:

$$\max_{\substack{x_{j,l}^{(i)}, P_{j,l}^{(i)}, R_{j,l}^{(i)}}} \left\{ \sum_{l \in L} \sum_{j \in T} \sum_{i \in C} x_{j,l}^{(i)} R_{j,l}^{(i)} \right\}$$
(3)
Subject to:

Subject to:

$$\sum_{j \in T} \sum_{l \in L} x_{j,l}^{(i)} \le 1, \qquad \forall i \in C$$
(4)

$$\sum_{i \in C} \sum_{l \in L} x_{i,l}^{(i)} \le M, \qquad \forall j \in T$$
(5)

where M is the OFDM factor that describes the maximum number of contiguous or noncontiguous frequency band that can be assigned for the same transmitter.

$$\sum_{i \in C} \sum_{l \in L} x_{j,l}^{(l)} \le L_j , \qquad \forall j \in T$$
(6)

$$\sum_{i \in C} x_{j,l}^{(i)} \le 1, \qquad \forall j \in T, l \in L$$
(7)

$$L = \sum_{i \in C} L_j , \quad \forall j \in T$$

$$SINR^{(i)} - u^* > (x^{(i)} - 1)y$$
(8)
(9)

(10)

$$C, \forall l \in L$$

where the constant $\gamma >> 1$.

This problem formulation is a mixed-integer nonlinear programming (MINLP) problem.

C. Solution (SMART-O)

Under the constraint below:

$$P_{j,l}^{(i)} = \begin{cases} P_{max}, when \ channel \ is \ idle \\ 0, \qquad Otherwise \end{cases}$$
(11)

We define a new variable (W) that describes all links $l \in L$ over all transmission requests $j \in T$: $W = \sum_{i} w_{i}$

where W is a number and wij is the number of links per transmission requests j, which can be found by the following relation:

$$w_j = \min\{L_j, M\}$$
(13)

In the light of the previous process, our problem formulation is:

$$max_{x_{w}^{(i)},r_{w}^{(i)}}\left\{\sum_{w}\sum_{i}x_{w}^{(i)}r_{w}^{(i)}\right\}$$
(14)

Such that:

$$\sum_{W} x_{W}^{(i)} \le 1 \quad , \forall i \in \mathcal{C}$$
(15)

$$\sum_{i} x_{w}^{(l)} \le 1 \quad , \forall w \in W$$
(16)

After doing that we start from SMART-V. We divide every packet to link, but we need to make its size D in KB.

Now, after we do the channel assignment, we sum D on every link and then try the first stage. The next stage of the sum of delays will be:

Next stage of the sum of delays = $\frac{D}{2Q}$ (17)where Q is the segmentation factor. Next, we will see how many packets it can send, and then if

time remains we do another stage until there will be no time remaining or it cannot serve another user.

After solving and performing the optimization, we will achieve the maximum sum-rate transmissions $r_i^{(i)}$, we are going to use this set to send the maximum data size in the time frequency unit. To do that, we firstly calculate the maximum data size $(D_i^{(i)})$ (in KB) of the CR transmission j that can be transmitted over channel i before the slowest rate transmission finishes, as follows:

$$D_{j}^{(i)} = \left[2^{Q} * \frac{r_{j}^{(i)}}{\min(r_{j}^{(i)})}\right] \frac{D}{2^{Q}}$$
(18)

where [x] finds the greater integer number that is equal or less than x. After defining the maximum data size, we want to take into consideration the data size of the CR user as follows:

$$D_j^{(i)} = L_j, \qquad \forall L_j < D_j^{(i)}$$
(19)

Figure 1 shows the residual time frequency blocks and how SMART-V MAC protocol (a) and SMART-O protocole (b) exploit these residual time frequency blocks.





(b)

Figure 1. The residual time frequency blocks and how SMART-V MAC protocol (a) and SMARTO protocol (b) exploit these residual time frequency blocks

And if $L_j < D_j^{(i)}$, check the opportunity of the available channel *i* then the first optimization stage is performed. The same process is performed for the next stage. This will continue as long

as $L_j < D_j^{(i)}$ and it will result in the k^{th} optimization stage $(O_i^{(k)})$ and reset the served CR transmissions. Other way to calculate the remaining time opportunity in channel *i* $(O_i^{(k)})$ is to take the time difference between the time required from the transmissions over channel *i* and the transmission with the lower rate. After the k^{th} channel assignment stage the value of $O_i^{(k)}$ is calculated as follows:

$$O_j^{(i)} = \begin{cases} \frac{D_j^{(i)}}{\min(r_j^{(i)})} - B_i & , \forall i \in C, \forall j \in T \\ 0 & , & otherwise. \end{cases}$$
(20)

where $r_j^{(i)}$ is the maximum rate over available channels C, T is the set of the transmission requests, and B_i is the busy period of the channel *i* in the current channel assignment, and it is

$$B_i = B_{i-1} + \frac{D_j^{(i)}}{r_j^{(i)}} \tag{21}$$

calculated cumulatively as follows:

After the first stage of optimization is done, the CR transmission requests are removed from the next channel assignment in the next optimization stage:

$$R_i^{(i)} = 0, \forall i \in C, \forall j \in T$$
(22)

And another constraint is added after the first optimization stage as follows:

$$\frac{D_j^{(i)}}{R_j^{(i)}} \le O_j^{(i)}, \forall i \in C, \forall j \in T$$
(23)

This is to guarantee that the time needed for the scheduled transmission is less than the available time.

Our protocol allows for time-scheduling which has great effect in increasing spectrum utilization by exploiting the unreserved residual time of channels assigned to CR users as shown in Figure 1 (a) and (b).

4. Channel Access Mechanism

The flowchart of our proposed scheme is shown in Figure 2.



Figure 2. Flow chart for the proposed MAC design

To enable our channel assignment in a distributed way, we propose a new channel access scheme. In our scheme, the aim is to maximize the sum-rate of all CR transmissions, and enhance the overall spectrum utilization by effectively exploiting the spectrum holes through smart scheduling and by the using D-OFDM under a given constraint. The proposed channel access scheme is based on optimum distributed channel-assignment scheme. Our proposed channel assignment requires information about the received SINR at CR transmitter, available channel set, and packet size. This information can be extracted from the exchanged RTS/CTS packets. Thus, no extra control overhead is needed to deliver this information. Control packets are exchanged over a dedicated control channel from the unlicensed band. Each AW consists of a number of access slots (AS). The number of access slots depends on the average number of CR transmission requests. Each AS duration is comparable to the sum of RTS, CTS, and maximum back-off time durations.

5. Results and Discussion

To properly asses the legitimacy of the proposed method, and to determine its feasibility to evaluate the performance, MATLAB software is used. Our proposed scheme is compared with the performance of the SMART-V protocol [12]. Our simulations are done with several variables under different scenarios. In this paper, our aim is to study the performance of the CRNs in terms of the system throughput.

A. Simulation Setup:

We use N pairs of one-hop transmitter-receiver users in a 100 meter \times 100 meter area. The locations of CR transmitter and recievers are randomly assigned within the network area. We conside *C* PR channels, each with 5 MHz bandwidth. For a fair comparison with SMART-V, we used the same setup described in [13]. The values of the simulation parameters used are summarized in Table 1.

Parameter	Value
Max. power (<i>Pmax</i>)	1 W
Thermal noise	10 ⁻²¹ W/Hz
SINR threshold	μ^*
Path loss exponent (<i>n</i>)	4
Number of experiments	30
Run time for each experiment	5000 time slts
Time slot length	100ms

Table 1. Simulation Parameters

The setup of the simulation which was modeled using MATLAB, included the identification of that a CRN with *N* CR nodes shares the same set of available sub-channels *C*. All CR nodes coexist in the same geographical area. The link rate is randomly generated. Some of the CR nodes will suffer from high interference all the time, and because of that, it will have the lowest data-link rates. Another set of CR nodes will suffer from moderate interference and that cause lowering the data-rate but not as much as the high interference affection. The last set of CR nodes will suffer from low interference. Zero link-rate means that the SINR at the receiver is below the SINR threshold. Our assumption is saturated network traffic. The packets are generated in the network with exponential random variable length and they are randomly assigned to CR users. We performed intensive simulations to evaluate the performance of our proposed channel assignment scheme and SMART-V performance as well.

These simulation results evaluate the performance of our proposed scheme (SMART-O) with SMART-V. Our case design is to enhance spectrum efficiency that can be achieved by maximizing network throughput, so we evaluate network throughput versus number of nodes and also versus number of channels.

B. Results and Discussion:

The evaluation of SMART-V MAC protocol for D-OFDM (SMART-O) transceiver-based CRN was performed using MATLAB software. The results were compared with SMART-V MAC protocol for conventional transceiver-based CRN. Figure 2 shows the performance of the SMART-V system without using D-OFDM and Figure 3 shows the performance of the SMART-V system with D-OFDM (SMART-O). These figures show the relationship of the throughput of each user vs. the number of available sub-channels with different number of nodes. In Figure 3, the throughput increases as the number of sub-channels increases. For N=10, the throughput will be stable with more than 15 sub channels system and the throughput will be almost 47 Mbps/user. In addition, for N=100 nodes, the throughput increases as the number of channels increase and it reaches up to 13 Mbps/user. Figure 4 is our proposed scheme (SAMRT-O) and it shows the relationship between the system throughput and number of channels. As shown, the throughput is increased compared to SMART-V system. In Figure 3, for N=40 and 100, the throughput of SMART-V system per user is 35 Mbps and 12 Mbps consequently. On the other hand, SMART-O in Figure 4 provides 72 Mbps and 36 Mbps for N=40 and N=100, respectively. That means using our proposed scheme results in better performance compared to SMART-V scheme.



Figure 3. Performance of SMART-V vs. number of channels



Figure 4. Performance of our proposed scheme vs. number of channels



Figure 5. Comparison between SMART-O and SMART-V with different number of nodes

In Figure 5, a comparison is made between SMART-O and SMART-V for different number of nodes. For N = 40, the solid green line (SMART-V) indicates the increasing of throughput as the number of channels increased until it reaches 29 Mbps/user for 25 channels. The dashed green line (SMART-O) indicates the increasing of throughput as the number of channels increased until it reaches 72 Mbps/user for 25 channels, which outperforms the SMART-V system.

Figure 6 shows the relationship of the throughput for the SMART-V system without using the D-OFDM system vs. number of nodes. The best performance is with number of sub-channels equal to 25. For 100 users, the throughput will be 12 Mbps/user.



Figure 6. Performance of SMART-V vs. number of nodes



Figure 7. Performance of SMART-O vs. number of nodes

Figure 7 shows the enhancements provided by the SMART-O system. The best performance is with number of sub-channels equal to 25. For 100 users, the throughput will be 37 Mbps/user.



Figure 8. Comparison between our proposed scheme SMART-O vs. SMART-V

In Figure 8, a comparison is made between SMART-V and SMARTO schemes. This figure shows how much enhancement to the SMART-V system is made using D-OFDM. For 25 subchannels, the SMART-V system throughput will be 12 Mbps with 100 nodes and for SMARTO system for the same number of sub-channels the throughput will be about 37 Mbps.

6. Conclusion

In this paper, we combined the multistage optimization (SMART-V) channel assignment scheme with D-OFDM technology. SMART-V channel assignment scheme exploits the residual time and the D-OFDM utilizes the spectrum using the orthogonality between sub-carriers. Using the D-OFDM technology, each user could reserve multiple sub-channels at the same time and could transmit the packets to multiple receivers.

SMART-O results in maximizing the overall throughput by maximizing the sum-rate of all the contending CR nodes and using lower rate sub-channels to save the bandwidth. It also uses the concept of aggregated channel. This is because each user could access into C sub-channels. The number and the location of these sub-channels will be different for each user. So, we use channel aggregation to combine m-sub-channels into one channel. The results show that SMART-O outperforms SMART-V by up to 250 %.

The proposed scheme also outperforms the D-OFDM based OPT-MAC system, because our proposed scheme exploits the residual time compared to OPT-MAC D-OFDM-based without using the SMAT-V MAC protocol.

Our proposed schemes greatly enhanced the network throughput. But, each user could access to one aggregated channel.

7. References

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