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An Opportunistic Two Transceiver Based MAC Protocol for Cognitive Radio Networks

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Abstract

Enormous growth of wireless applications makes the spectrum scarcity problem worse day by day. Moreover, traditional fixed spectrum assignment policy causes serious spectrum underutilization problem. However, Cognitive Radio that enables opportunity based spectrum access for unlicensed users has recently been recognized as a heartening solution for spectrum scarcity and underutilization problem. Medium access control protocol is the key enabler or coordinator for this opportunity based channel access. However, recent studies show that in distributed cognitive radio networks MAC protocol suffers from severe performance degradation due to common control channel selection (CCC) problem, the multichannel hidden terminal problem (MHTP). In this paper, we propose a MAC protocol that eliminates CCC selection problem. Here, unlicensed users use dedicated band owned by them as a common control channel. Every unlicensed user equipped with two transceivers. One is control radio that helps SU's to get updated control information and other is data radio. This clearly cuts down the number of collisions with other secondary and primary users in data transmission phase. To obtain the accurate sensing result, we propose cooperative sensing for idle channel detection. In this paper, we develop an analytical model to analyze important performance metrics. Simulation results show the effectiveness of our system.

Keywords: *Cognitive Radio Network, Medium Access Control(MAC), Cooperative Sensing*

1. Introduction

Spectrum resources are becoming more and more restricted by the emergence of diverse wireless devices and applications. With fixed spectrum allocation policies, most of the spectrum is underutilized due to time varying requirement of spectrum by users or services. Primary user's spectrum (licensed) remains unused, if it is not used by a primary user since it cannot be utilized by any other secondary user (unlicensed user). According to the Federal Communications Commission (FCC), spectrum utilization for fixed channel assignment scheme varies from 15% to 85% [1]. Thus, the use of spectrum is typically low on space and time. To support emerging wireless applications, spectrum should be utilized properly. Otherwise, spectrum scarcity problem arises because most of the spectrum has already been allocated. Cognitive radio (CR) has recently been identified as a promising technology to solve spectrum scarcity problem by opportunistically utilizing the unused primary user spectrum. This promising technology allows a group of unlicensed secondary users (SU's) to opportunistically access frequency bands originally allocated to primary users (PU's). Secondary users sensing the primary users channel to find an idle channel for data

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transmission [2]. Spectrum utilization can be significantly amended by allowing opportunistic spectrum access to secondary users (unlicensed).

Medium Access Control (MAC) protocol provides control and coordination of channel access mechanisms that enable secondary nodes to access the spectrum in contention with other secondary users, and to coexist with primary users. Recently several MAC protocols were made for CR networks. In distributed cognitive radio networks (CRN), the design of a MAC protocol largely depends on the number of transceiver needed at each SU node to support the MAC operations. Some of the MAC protocols (*e.g.,* [5-8]) work well with a single transceiver, while some (*e.g.,* [4, 9, 10]) need multiple transceiver at SU nodes. An SU equipped with a single transceiver/radio can listen to only a single channel at a time, and therefore can miss control messages when its transceiver is busy transmitting or receiving data. As a result single transceivers MAC are more vulnerable to MHTP [3]. MHTP becomes easier to handle with multi transceiver MAC. However this necessitates a common control channel for exchanging the sensing information and reserving the channel before data transfer [11]. Most of the existing MAC protocols are designed assuming the presence and absence of a CCC. Reliance of a CCC however lead to a phenomenon called CCC saturation. Without a CCC, MAC design becomes more challenging because there is no predefined channel to start the exchange of control messages. DC-MAC [5] and SYN-MAC [4] are proposed to work without a CCC for single and multi transceiver systems, respectively. The exchange of control messages in these MAC protocols is usually performed on PU data channels, and is not reliable or efficient. Traditionally, broadcasting has been overlooked by many of the non-CCC based multichannel MAC protocol. Using a CCC, broadcasting can be done very efficiently [12]. CREAM-MAC protocol proposed in [13], employs a common control channel as rendezvous where the SUs exchange the control packet for resource reservation. Time synchronization becomes an important issue for single radio MAC designed with a CCC [*e.g.,* HC-MAC, OSA-MAC, and C-MAC]. This can be achieved either local or global time synchronization. Some MAC such as HC MAC works with local time synchronization, which could result in the exposed terminal problem as mentioned in [7]. In C-MAC [8], a complicated mechanism to reconfigure the dynamic global CCC increases its reconfiguration overhead. To avoid node complexity some proposals assume single radio per node & circumvent MHTP using a global common control channel. CSMA based MAC protocol proposes to negotiate a favourable channel between sender and receiver pair. Without channel sensing information CSMA based MAC [15] cause several interference to PU's. On the other hand OSA MAC [6] inserts a sensing phase after the contention based channel selection phase. Since channel selection phase is done before channel sensing, nodes might end up selecting unavailable channels thereby wasting transmission opportunities. HC MAC proposed in [7], performs channel sensing before the channel selection also considers hardware limitations of practical SU nodes. Our proposed protocol can empower CR devices with the following capacities: (i) each secondary user is equipped with two transceivers. One transceiver is used for hearing control channel information other transceiver is used for sensing and data transmission; (ii) Dedicated control channel is proposed for secondary users (owned by them); (iii) Multichannel hidden terminal problem is solved under our proposed MAC protocol; (iv) A contention based protocol such that every secondary user gets same chance to access the unused primary channel; (v) Cooperation among secondary users is considered. As far as we notice, there is no existing MAC protocol which incorporates the above virtues concurrently.

The rest of this paper is organized as follows. In Section 2, we introduce the system model. In Section 3, proposed scheme are illustrated. In Section 4, analytical model are discussed. Simulation results are given in Section 5, and finally we conclude this paper in Section 6.

2. System Model

A WSN is a special network which has many constraints compared to a traditional computer network. We consider the scenario where there are two types of users. Secondary users licensed spectrum opportunistically when channel is vacant.

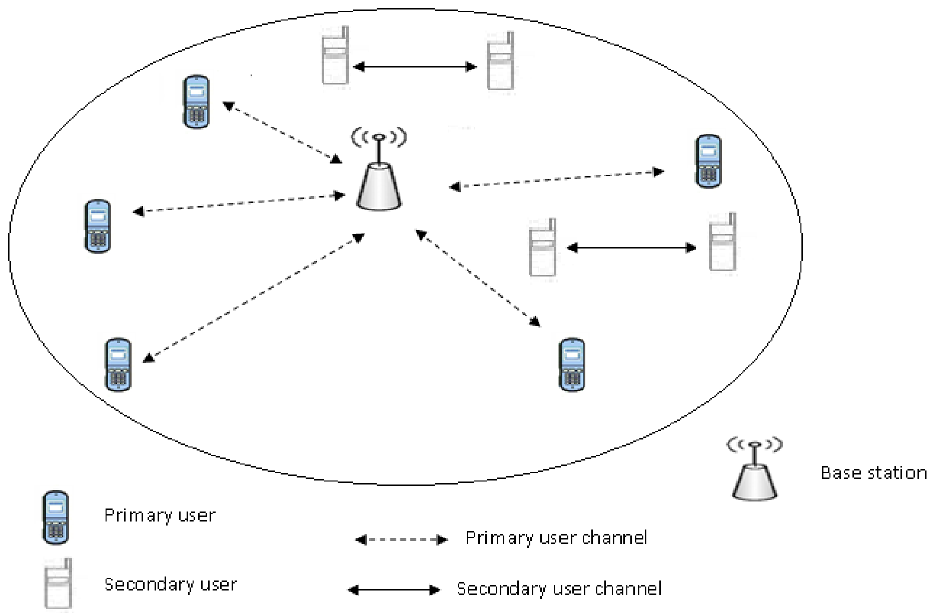

Figure 1. Proposed System Model

The dashed dotted line indicates licensed primary users channel. The solid line indicates opportunistic secondary user's channel. The common control channel and transceivers of secondary user's is not shown in the Figure 1 for simplicity.

The proposed system model is shown in Figure 1. We consider N orthogonal licensed channels for secondary users. All licensed channel have the same capacity. Secondary user's sense and use that channel if vacant to communicate other secondary node within the communication range. Every secondary node is assumed to be equipped with two radios. One of the two radios is used for just listening to the control signals (listening radio) and the other radio for receiving and transmitting data. Consider primary networks consisting of N non-overlapped channels numbered from based on its sequence in the spectrum. Each channel of the N licensed channels can be modelled as ON/OFF source. The secondary network consists of M total number of secondary users seeking for spectrum opportunities over the N licensed channels. In order to exchange their control messages, the SU uses common control channel (CCC) dedicated to them. The CCC can be either a channel in unlicensed bands or a channel licensed to the SUs. To avoid MHTP problem, we have proposed dedicated CCC for secondary users and two transceivers equipped such that secondary users always tune to the common control channel.

3. Proposed Medium Access Control Protocol

In the proposed MAC protocol SU's opportunistically use licensed users spectrum. Figure 2 shows the timing structure of our proposed scheme.

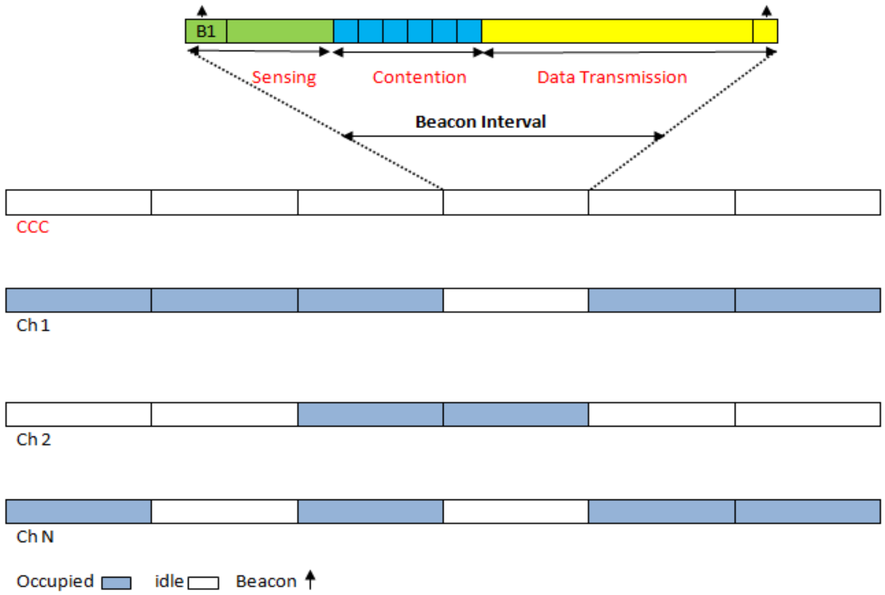

Figure 2. Proposed Timing Structure Model

The protocol assumes dedicated common control channel owned by cognitive radio users for efficient control signal exchange. That is common control channel is always available to secondary users. Global time is divided into periodic beacon intervals in which we can divide three phases: sensing, contention and data transmission. Secondary users are synchronized by periodic beacon messages. During the sensing phase, every secondary user's sense and exchange sensing result among other SU's. This sensing policy assists to identify which and how many channels are available to be used by the SU's. The throughput of the secondary network is expected to increase based on efficient sensing result. Cooperative sensing policy allows the sharing of sensing result to improve insufficient idle channels for each unlicensed user. After that SU's participate in contention phase to reserve idle licensed channels for data transmission. Proposed design of contention phase can efficiently address MHTP because it provides smart coordination among neighbours during channel reservation process. We have proposed two transceivers MAC, such that every secondary node can sense/transmit and hear control information at the same time. That can improve overall throughput of secondary users. Whenever a channel is reserved by a sender-receiver pair, all nodes all nodes which are neighbours of sender-receiver pair set network allocation vector for the channel. An unsuccessful node goes into a back off state waits for next turn. Data transmission occurs between sender and receiver during data transmission phase based on channel reservation. If the transmitter does not receive acknowledgement, it will consider the data transmission unsuccessful. If any PU arrives SU's must vacate the channel. We have found that, using the proposed MAC model collision with SU's in data transmission phase reduced dynamically. Consequently, SU's system throughput can be maximized.

4. Analytical Model

A s saturation throughput is a major performance measure to evaluate MAC protocols, we analyze it in this section. We have assumed that N_{avg} is the average number of channel reserved during contention phase based on our proposed MAC protocol. We also assumed that T_{DT} is the length of data transmission phase and T_{BI} is the beacon interval duration. We adopt an overlay model where secondary nodes opportunistically access the idle channel originally licensed to primary users. Over time, the occupancy on a given licensed user channel is assumed to follow Bernoulli distribution. SU's exchange control messages on the common control channel using an access mechanism similar to IEEE 802.11 DCF during the contention phase. Let the approximate upper bound on average saturation throughput can be expressed as:

$$S_{avg} = \frac{T_{DT} * N_{avg}}{T_{BI}} \quad (1)$$

For simplicity, we take for granted that only the average access of any channel over particular time is exposed and is equal to (1-P_j), where P_j is the average probability of channel j being free from primary user use. Let us assume that, Tsensing is the time required for sensing phase and Tcon is the time required for contention phase. We can write that data transmission duration is equal to T_{DT}= (T_{BI}-$T_{sensing}$-T_{con}). We have assumed that average length of successful message exchange for channel negotiation is denoted as T_{SI}. During contention phase time slot may be idle, unsuccessful or successful. Now average saturate throughput can be expressed as:

$$S_{avg} = \frac{N_{avg} * (T_{BI} - T_{sen\sin g} - T_{con})}{T_{BI}} \quad (2)$$

So, expected number of successful message exchange during contention phase can be denoted as:

$$N_s = \frac{T_{con}}{T_{SI}} \quad (3)$$

Therefore, average number of channel (N) that can be reserved during contention phase is given by

$$N = \sum_{i=1}^{N_{ch}} C_i * \min(i, N_s) \quad (4)$$

$$C_i = \binom{N_{ch}}{i} P_i (1 - P)^{N_{ch} - i} \quad (5)$$

Now average saturation throughput per beacon interval can be calculated as follows

$$S_{avg} = \frac{N * T_{DT} * R}{T_{BI}} \quad (6)$$

Where, R is the data rate per channel. Maximum throughput is reached if contention time just enough to reserve all channels. After that, throughput decreases with increasing contention time. In the proposed MAC protocol, a SU senses and shares the sensing result during sensing sharing phase. It is assumed that sensing time is *l* and total time frame duration is T. Therefore, false alarm probability (P_f) and detection probability (P_d) at each secondary user can be written as [16]:

$$P_f = Q\left(SNR \sqrt{\frac{l * f_s}{2}} + Q^{-1}(P_d)\sqrt{1 + 2SNR} \right) \quad (7)$$

$$P_d = Q\left(\frac{Q^{-1}(P_f) - SNR \times \sqrt{\frac{l * f_s}{2}}}{\sqrt{(1 + 2SNR)}} \right) \quad (8)$$

where signal to noise ratio $SNR = P_s / \sigma_v^2$ and f_s is the sampling frequency. Let the hypotheses H_0 and H_1 occur with probabilities $P(H_0) = P_{idle}$ and $P(H_1) = P_{busy}$, respectively. It is assumed that D is the channel access delay per sensing time and K is the contention time for channel reservation. Then, for non cooperative sensing, channel access delay caused by following three cases: (1) Channel access delay for correct detection; (2) Channel access delay for false alarm; (3) Channel access delay caused by sensing and contention phase. Then the average channel access delay can be written as follows:

$$D_l = l + k + [P(H_1) \times P_d(l) + P(H_0) \times P_f(l)] \times (T - l - k) \quad (9)$$

We have proposed cooperative sensing policy for our MAC model such that SU's cooperatively sense the spectrum and share the result. Such cooperation reduces sensing delay and sensing error. It is assumed that M is the number of cooperating users, K is the contention time duration, and t_r is the time used in reporting. When the sensing results are transmitted to CCC, majority rule is used to obtain the presence and absence of the PU. Thus, joint probability of false alarm and detection can be obtained by:

$$Q_f = \sum_{i=n}^{M} \binom{M}{i} P_f^{\,i} (1 - P_f)^{M-i} \quad (10)$$

$$Q_d = \sum_{i=n}^{M} \binom{M}{i} P_d^{\,i} (1 - P_d)^{M-i} \quad (11)$$

Missed detection probability is equal to ($1 - Q_d$). Then the average channel access delay for SU's can be written as follows:

$$D_l = l + k + Mt_r + [P(H_1) \times Q_d(l) + P(H_0) \times Q_f(l)] \times (T - l - k - Mt_r) \quad (12)$$

In the following section, we will demonstrate the simulation results to validate our analytical model.

5. Simulation Results

In this section, we present the simulation results to study the performance of our proposed medium access control protocol. The simulation scenario is shown in Figure 4. To evaluate system throughput of SU's based on our analytical model, expensive computer simulations have been conducted. We compare the following three schemes in our simulations: Single transceiver MAC with CCC, Traditional CCC based MAC, & Our Proposed MAC. Some of the proposed MAC protocols named as single transceiver based MAC (*e.g.,* [5-8, 16]) work with a single transceiver. Single transceiver MAC can listen only one channel at a time, therefore when they are busy with sensing or data transmission can miss control messages. Single transceivers MAC is prone to multichannel hidden terminal problem (MHTP). Some of the proposed MAC protocols named as traditional

Figure 4. An Instance of a Simulation Environment

Traditional CCC based MAC (*e.g.,* 9, 10, 6, 14, 16) work with a common control channel can be either dedicated or dynamically configurable. This type of MAC protocol suffers from CCC selection problem. Merely it is really hard to select PU's channel as a dedicated control channel because of PU's traffic active at whatever time. We let N_{ch} =5, R=1mbps, l=5ms, T_{BI}=100ms. In Figure 4 we assume that 10 primary nodes and 20 secondary nodes uniformly distributed in a 200m x 200m square area. The channel coefficients between nodes are modelled as a zero-mean complex Gaussian random variable with variance close to unity. We have done our simulation for 5 primary user channels. In Figure 5, we vary the contention time from 0 to 100 to vary throughput. After the required contention time, increase of contention time negatively affect throughput.

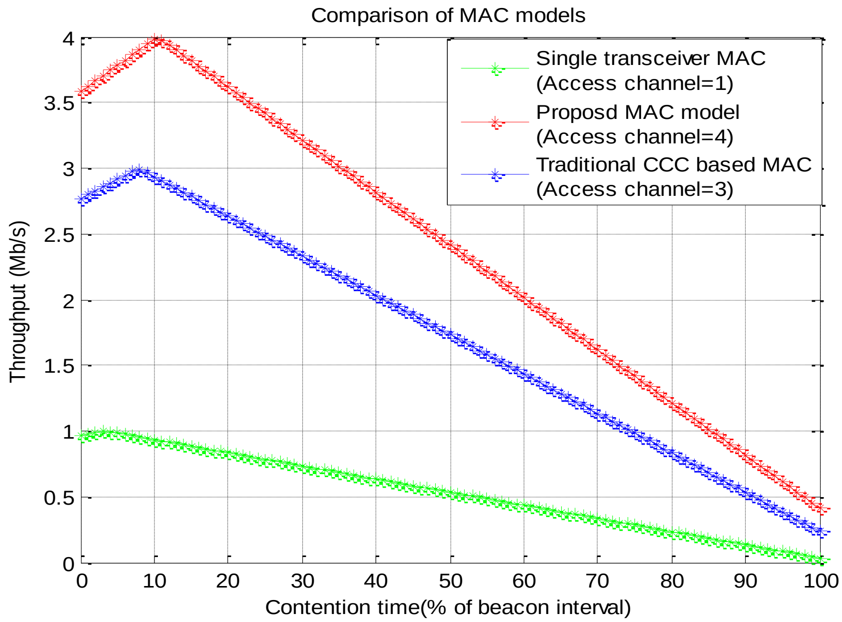

Figure 5. Comparison of Throughputs for Several MAC Models vs. Contention Time

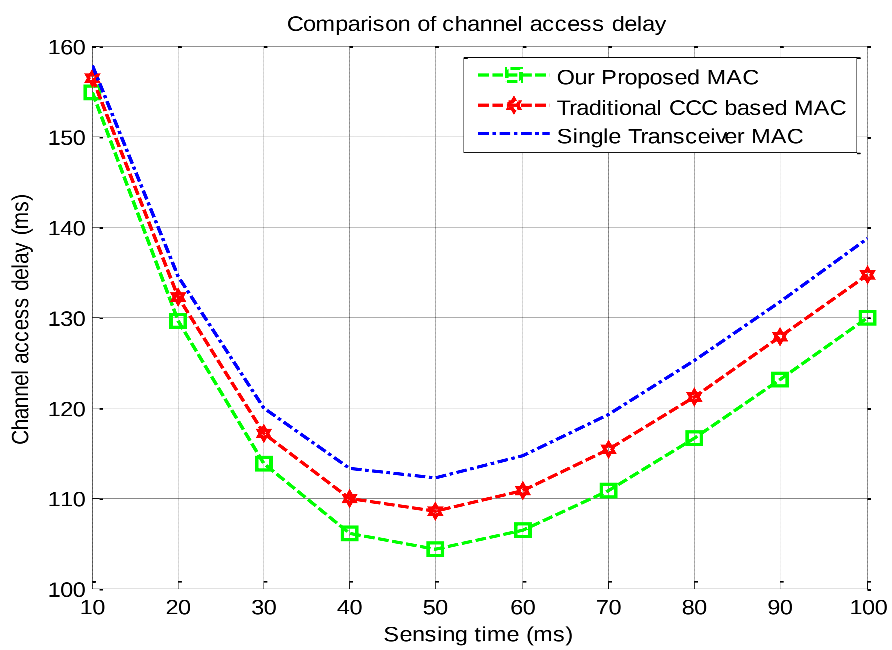

Figure 6. Comparison of Channel Access Delay Versus Sensing Time (for SNR= -2 dB, Time Frame Duration T=200 ms)

The throughput performance of our proposed MAC is compared with other two generalized MAC models existing in the literature. We can also say that our MAC protocol shows improved throughput than other two mentioned MAC protocols. Figure 6 shows that for a given sensing time proposed protocol improves the performance of channel access delay. It is also expected that lower channel access delay leads to higher spectrum utilization. We let $P(H_1)=0.3$, $P(H_0)=0.7$, $M=20$, $f_s=1000Hz$, $t_r=20\mu s$. Note that the false alarm value decreases with the increase of sensing time values.

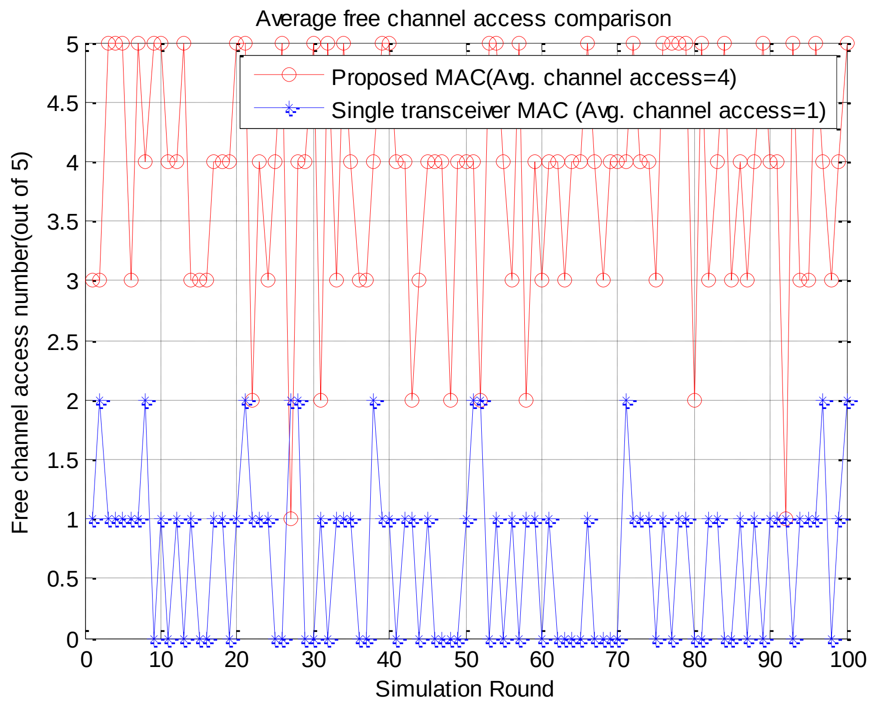

Figure 7. Comparison of Total Channel Access per Simulation Round

In Figure 7, we investigate the impact of free channel access per simulation round for both proposed protocol and single transceiver MAC protocols. We can easily state that our proposed protocol shows improved throughput than single transceiver MAC protocols. It has been testified that for a given sensing time proposed protocol improves the performance of channel access delay. It is also expected that lower channel access leads to higher spectrum utilization. We concentrate on the contention time duration to analyze channel access delay.

By comparing the outcomes we can easily state that because of collision in data transmission phase contention time increases to reallocate each free channel observed in sensing phase. We have discussed and presented simulation results to evaluate the performance of our proposed MAC protocol. It is shown that, proper channel allocation policy proposed in our MAC protocol not only improves the throughput or spectrum utilization of secondary users but also decreases the collision probability to SU's at data transmission phase and PU's. The performance of our proposed protocol and other traditional protocol like CCC based & single transceiver MAC protocol are compared in terms of throughput and channel access delay. We have presented a MAC protocol for distributed cognitive radio network which avoids the need for selecting common control channel for control signal exchange among idle primary user data channel. This automatically eliminates CCC selection problem and achieves better coordination.

6. Conclusion

Our aim is to provide an efficient channel access policy for secondary users. Many issues in channel selection or access control remain open and we expect to see more research activities on these exciting topics in the future. In this paper, we have proposed an opportunistic medium access control that ameliorates the spectrum access for cognitive radio users. We investigate the design problems of medium access control protocol design for secondary users to revamp overall throughput under the restriction of adequate safety to primary users. Our proposed protocol plausibly avoids collision among secondary users in data transmission phase. We show by simulations that our proposed MAC protocols provide higher throughput and lower channel access. delay than other mentioned protocols. Moreover, in our proposed MAC protocol CCC is always known to secondary users. Thus, our proposed protocol provides strong network reconfiguration and time synchronization. Our proposed model is fruitful in permitting multiple secondary users to transmit their data effectively on multiple channels. The evaluation comprehensibly reveals that our proposed MAC protocol is beneficial for multichannel cognitive radio networks. In future, we need to develop more practical PU activity models by considering the characteristics of access technologies as well as traffic types. Intelligent spectrum sharing, sensing, the power allocation policy may improve QoS in CR networks

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