A MAC Protocol for Cognitive Radio Networks with Reliable Control Channels Assignment

Zaw Htike , Jun Lee and Choong Seon Hong
Department of Computer Engineering, Kyung Hee University,
1 Seocheon,Giheung, Yongin, Gyeonggi 449-701 Korea
htike@networking.khu.ac.kr,
junlee@networking.khu.ac.kr,
cshong@khu.ac.kr

***Abstract*—In cognitive radio network, control information dissemination is critical. Secondary users need to exchange control information for utilizing the available channels efficiently, to maintain connectivity, to negotiate for data communication such as sender-receiver handshakes, for neighbor discovery etc. In currently proposed MAC protocols for cognitive radio networks, control information are disseminated among users by using two famous mechanisms. The first one is the use of common control channel (CCC) and the second one is using channel hopping. However, both methods have their own drawbacks. The use of CCC may not be feasible in cognitive radio networks as the available channels, including control channel, are dynamically changing according to primary users activities. Channel hopping approaches cause significant amount of channel access delay which is known as time to rendezvous (TTR). In this paper, we propose a hybrid protocol of these two mechanisms. This hybrid protocol can maintain connectivity among secondary users by using multiple control channels. The use of multiple control channels guarantees the secondary users to be able to exchange control information in dynamic environment. Channel hopping is performed only for control channels, so it provides relatively small amount of channel access delay.**

***Index Terms*—Cognitive radio networks, reliable control channels**

I. Introduction

Cognitive radio technology seems to be a new way to compensate the spectrum shortage problem of wireless network environment. In CR networks, secondary users (SUs) are allowed to use free portions of licensed spectrum or channel in opportunists fashion without causing any interference to primary users (PUs). All SUs need to scan and detect the spectrum holes or free channels to utilize. These sensing results should be exchanged among SUs to be more reliable and accurate as available channels are dynamically changing according to PU activities [1]. One more important thing is SUs need to negotiate by exchanging control information (such as RTS/CTS in 802.11 DCF) to establish data communication on a common channel. Therefore, control packets exchange among SUs is vital in cognitive radio networks.

This research was supported by Next-Generation Information Computing Development Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology (No.20100020728). Dr. CS Hong is the corresponding author.

A. Motivation

As mentioned above, spectrum utilization and resource optimization rely on information exchange among secondary users. However, this introduces the most remarkable challenge, how the SUs can exchange these control information in ever-changing dynamic environments.

Generally, the necessary information is embedded in control packets and these are exchanged via a channel with assumption that this channel is available for every user in the network. This channel is called common control channel (CCC) and all SUs use it for control packet exchanging and negotiation [2][3]. In this approach, when a SU wants to initiate any communication, it switches to CCC first and attempts to negotiate with intended receiver. After negotiation has been done on CCC, data communication can be accomplished in other available channels known as data channels [4][5]. Fig.1 illustrates the normal operation of a network with a common control channel. In contention phase, all nodes attempt to negotiate on CCC . After negotiation has been done on CCC, nodes[1] move to selected channels and perform data communications simultaneously.

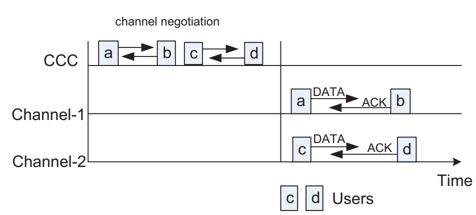

Fig. 1. Process of channel negotiation and data communication with a common control channel

However, establishing a constantly available CCC in CR networks is great challenge due to the following reasons. (1) Since all nodes use only one CCC for exchanging control packets, the control channel may be congested and it can cause single point of failure. This is called *control channel saturation problem* [6]. (2) When a PU appears on CCC, all SUs must defer their transmissions and vacate the channel immediately. If the period of primary user's transmission is significantly long on CCC, the presence of PU may block the SUs to access

[1]In this paper, we use the terms, node and secondary user interchangeably

the channel. It will definitely degrade the overall throughput of CR network. (3) In CR networks, the available channels are dynamically changing including the CCC. Therefore, an ever-available control channel for all SUs is unlikely to exist.

Channel hopping protocols have been proposed to compensate the problems of CCC. In this approaches, SUs generate their own channel hopping sequences. When a SU needs to communicate with its neighbors, it switches one channel after another by following hopping sequence and finds its neighbors. When two SUs (sender and receiver) rendezvous on a common channel, they exchange control packets and negotiate for data communication[7][8]. Fig.2 illustrates the operation of a channel hopping protocol. In Fig.2, user *a* and *b* find each other by following their own hopping sequences. When they meet on channel 3, they perform negotiation for data communication.

The main advantage of these approaches is SUs can rendezvous on every available channel. Therefore, it can overcome control channel saturation problem and tolerate long term blocking of primary users. Moreover, channel hopping protocols consider only pair-wise rendezvous (only a sender and a receiver), so these do not need a global available common control channel.

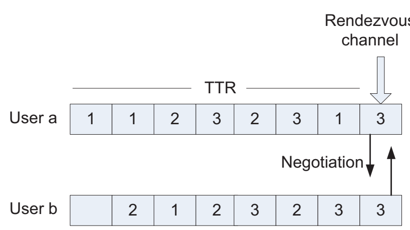

Fig. 2. Operation of a channel hopping protocol

However, the main drawback of channel hopping (CH) approaches is channel access delay. In CH protocols, whenever a SU needs to initiate any communication with its neighbors, it has to find its neighbor by switching one channel after another. SU needs significant amount of time to find its neighbors and it is, normally, called time to rendezvous (TTR). The value of TTR depends on channel hopping algorithm. The authors of [7] proposed permutation-based channel hopping sequence. In their proposal, the expected time to rendezvous is bounded by quadratic function of the number of available channels. A quorum-based scheme was proposed in [9] and the authors claimed that rendezvous between any pair of nodes can occur at least once within N^2 time slots, where N is number of available channels. As we have seen, the TTR value highly depends on number of available channels. Therefore, in channel hopping protocols, nodes may take a long time to find its neighbors for control packets exchange, especially when the number of available channels of the network is large [10].

In this paper, we propose a hybrid protocol of above two mechanisms. In our proposed protocol, we use multiple control channels rather than one CCC. If some control channels are unavailable in case of PU activities, SUs still can use other free control channels, so it can tolerate long-term blocking of primary users. SUs can negotiate on different control channels independently and this can overcome control channel saturation problem. Channel hopping is performed only for control channels, so that TTR value is relatively small. Moreover, it does not need to generate channel hopping-sequence but SUs just need to memorize the list of control channels, so it provides less complexity.

TABLE I
LIST OF NOTATIONS

Term	Definition
N	Number of available channels
M	Number of control channels (Number of channel groups)
G_i	Channel group i
C^i_{list}	Free channel list of group i
C^i_l	Channel l which belongs to group i
CC_{list}	List of control channels
CC_i	Control channel i

II. PROPOSED PROTOCOL

A. Control Channels Establishing

We assume that there are N number of available channels in the network. These are divided into M number of groups which are $G_i \subseteq N, (i = 1, 2, 3, ..., M)$. None of the available channels is overlapping in any two groups, which means $G_i \cap G_j = \phi, i \neq j$. One channel of each group, $(CC_i \in G_i)$, is selected as a control channel. Therefore, in the set of control channels, there are M number of control channels that is $CC_{list} = \{CC_1, CC_2, CC_3, ..., CC_M\}$. This control channel list is stored in every node of the network. In Table.1, a list of notations is presented.

B. Channel Access Mechanism

Every node in the network could be one of the following states in any time.

- Active state: Node has data to send to other nodes .
- Passive state: Node has no data to send.

If a node is in active state which implies it has some data for other nodes, so it switches one control channel after another without repeating $(CC_i \in CC_{list}, \forall i \in CC_{list})$ and attempts to rendezvous its intended receiver. When it switches to a control channel, it senses the channel for the presence of PU and other SUs' transmission. If it senses the channel is free, it probes whether its intended receiver is on current channel by broadcasting a preamble (PRE). Preamble is a small packet and it contains only receiver's address. After transmission a PRE, the node waits for an acknowledgment (ACK). All transmissions follow the principle of 802.11 DCF [11]. Then total interval of this process is defined as one time slot (T_{slot}) and it can be estimated as

$$T_{slot} = \frac{PRE + ACK}{T_{rate}} + DIFS + SIFS + B \quad (1)$$

,where T_{rate} is transmission rate and B represents the random back-off. While active node is waiting ACK, it might also receive PRE with its address. If it receives PRE instead of ACK, it will reply ACK and perform channel negotiation.

If active node does not receive any acknowledgement (ACK) from the receiver, it shall switch to another control channel and broadcast preamble again. This process is repeated until it has received AKC from the receiver or it has switched all control channels. The necessary time for active node to switch and find its intended receiver on every control channels can be estimated as

$$T_{round} = T_{slot}.M \tag{2}$$

where M is number of control channels. If the node cannot rendezvous with the receiver on any control channel, its receiver might be currently communicating with other nodes on a data channel or it might be in active state either. Therefore, when an active node has spent a T_{round} without receiving any ACK which means no meeting with its intended receiver, it will choose active state for next T_{round} with probability P_{active}. The optimal value of P_{active} is described as 0.7525 in [12].

If a node is in passive state, it chooses one control channel ($CC_i \in CC_{list}$) and tunes its radio on receiving mode. While it is in passive state on control channel CC_i, it performs periodic sensing for all available channels which belong to G_i and makes a free channel list (C^i_{list}) of group i. Periodic sensing is performed by passive nodes and as soon as it senses primary user signal on current control channel, it will switch immediately to another control channel. If a passive node does not get any preamble from its potential sender, it is possible that the current control channel is not available for the sender or it is too congested and the PRE cannot be sent. Therefore, if a passive node spends T_{round} without receiving any PRE, it will choose another control channel $CC_j \in CC_{list}$ and wait one T_{round} again. If it receives preamble from its sender, it will simply reply ACK and these two nodes can continue channel negotiation on current control channel by exchanging necessary control packets.

C. Channel Negotiation

If two nodes rendezvous on a control channel, they can perform channel negotiation. In negotiation phase, sender sends RTS to receiver as traditional 802.11 DCF. Receiver chooses one channel from its free channel list which is $C^i_l \in C^i_{list}$ and replies it with CTS. After exchanging control packets (RTS and CTS), these two nodes switch to C^i_l and perform data communication. Other neighbor nodes which are currently on CC_i can overhear CTS from the receiver, so that they remove C^i_l from their C^i_{list}. Therefore, any node which overhears the CTS can avoid interference to neighbor nodes' data communication and this can overcome multichannel hidden terminal problem.

The detailed process of channel access negotiation is illustrated in Fig.3. Secondary user a and user b rendezvous on CC_i and a transmits RTS to b. SU b selects C^i_2 and replies it with CTS. Then a and b move to C^i_2 and perform data communication. SU e is currently on CC_i and it can overhear CTS from b. It can know that channel C^i_2 is going to be used by neighbors, so that e modifies its free channel list as $C^i_{list} = C^i_{list} \setminus C^i_2$. While a and b negotiating on CC_i, SU c and d can negotiate on CC_j simultaneously. Therefore, it can significantly reduce control channel saturation problem. Moreover, in case of PU appears on one of those control channels, SUs still can negotiate on different control channel and maintain the connectively of the network.

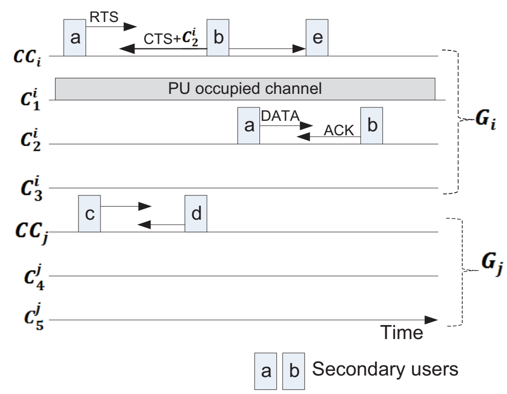

Fig. 3. (a) Channel grouping and negotiation

III. Performance Evaluation

A. Connectivity

Secondary users are allowed to use only free or idle potions of channels. Fig.4 shows an example of PU activities on a channel. Transmission opportunities of a channel happen when

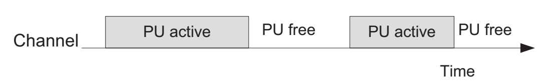

Fig. 4. PU activities on a channel

the PU does not use it. Average transmission opportunity for SUs on channel k is

$$P^{idle}_k = \frac{\sum PU_{free}}{\sum PU_{active} + \sum PU_{free}} \tag{3}$$

where PU_{active} refers PU occupied period of a channel and PU_{free} represents idle period. Average transmission opportunity for SUs is

$$E[T_{opp}] = \frac{1}{N}\sum_{k=1}^{N} P^{idle}_k \tag{4}$$

We plot the average transmission opportunity for SUs in Fig.5. We assume that there are five primary users in the network and PUs can appear on any available channel in any time. We define various primary user activities (average PU_{active}) as 0.7, 0.5 and 0.3. As shown in Fig.5, the average

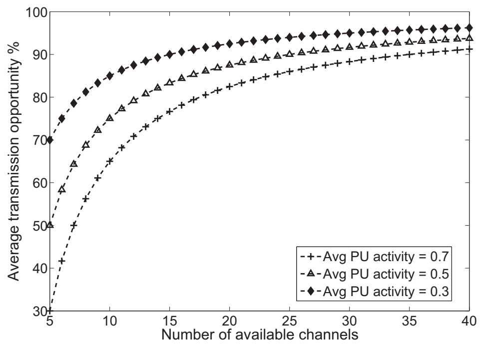

Fig. 5. Average transmission opportunity for SUs under different available channels

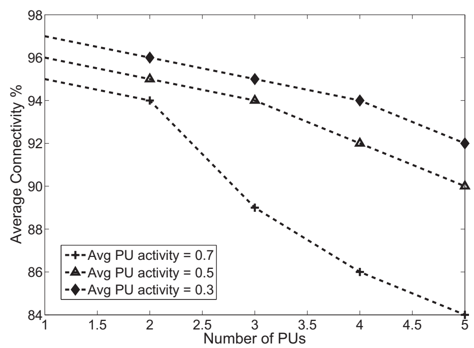

Fig. 6. Connectivity of network against number of primary users

transmission opportunity for SUs increases as the number of available channels increases.

Actually, the connectivity of CR network is determined by the availability of control channels and it can be described as

$$E[T_{opp}^{CC}] = \frac{1}{M} \sum_{k \in CC_{list}} P_k^{idle} \quad (5)$$

To measure the connectivity, we ran simulations on $Omnet++$ simulator. We assign 20 available channels $(N = 20)$ and 4 control channels $(M = 4)$. It is assumed that PUs can appear on any channel randomly and connectivity is measured based on availability of control channels. We ran simulations 100 times and take the average value. The results of connectivity against number of PUs are presented in Fig.6.

B. Collision Rate and Throughput

In proposed hybrid protocol, SUs need to rendezvous their neighbors on one of control channels and negotiate for data communication. Therefore, collision rates depend on how many users attempt to negotiate on control channels. We simulate our mechanism to measure the control packets collision rate against the number of SUs in the network, as well as the number control channels. In this scenario, the number of primary users is set to be five and average PU activity is 0.5. Number of available channels is defined as 20 $(N = 20)$ and SUs are randomly distributed on different channels independently. The control packets (RTS/CTS and PRE/ACK) sizes are defined as 160 bits. After a sender rendezvous with its intended receiver on a control channel, it will attempt to negotiate for data communication as described in section 2.2. When collisions occur, SU retries to negotiate. We assumed that collisions occur when two or more nodes transmit the control packets at the same time. There are two possible way of occurring collisions. The first one is two or more nodes sense the channel as free at the same time. The second one is back off time (B) of two or more users reach to zero at the same time.

Simulation results of normal CCC approach and proposed hybrid protocol with various control channel assignments can be seen in Fig.7.

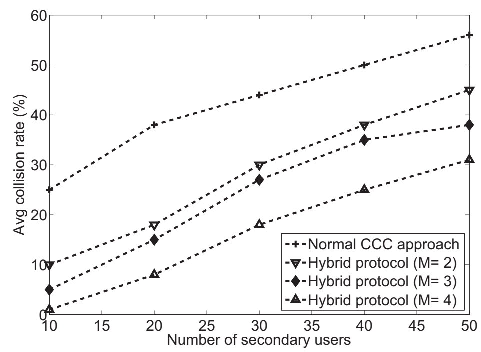

Fig. 7. Control packets collision rates against various numbers of SUs and control channels.

In normal CCC approach, one of the available channels is assigned as common control channel and the rest are used for data communication. When the number of users increases, collision rate of normal CCC approach also increases, because all nodes use only one control channel for negotiation. However, as shown in Fig.7, we can reduce the collision rate by using multiple control channels. The collision rate of hybrid protocol with two control channels or two channel groups is almost 50% less than that of normal CCC approach.

The control packets collision rates determine the throughput of the network because data communications can be accomplished only after successful negotiations. We can assume that, there are no data packet collisions among SUs because of the procedure we presented in section 2.3. However, if a PU appears on current data channel, SUs defer the current transmission and switch to the previous control channel for re-negotiation. Throughputs are measured for data packets only and packet sizes are randomly assigned between 512 bytes -1024 bytes. The transmission rate is set to be 11 Mbps. Fig.8 presents the throughputs of normal CCC approach and hybrid protocol with various control channel assignments. The collision rate increases as the number of users in the network becomes large and it degrades the average throughput of each user. However, as shown in Fig.8, we can achieve the desirable throughput by using multiple control channels.

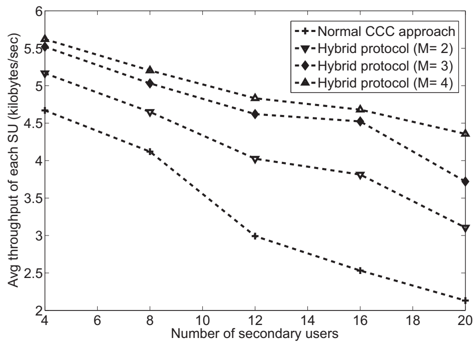

Fig. 8. Throughputs of normal CCC approach and hybrid protocol with various control channels assignments.

IV. Conclusion

In this paper, we have presented a hybrid MAC protocol for cognitive radio ad hoc networks. The proposed hybrid protocol can be more tolerable primary user activities than traditional CCC approach. Moreover, it can overcome control channel saturation problem. Simulation results validate that the hybrid protocol outperforms the previous works in term of throughput and control packets collision rate. As a future work, we will develop our protocol for multi-hop networks.

References

[1] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, "CRAHNs: Cognitive radio ad hoc networks," *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, July 2009.

[2] X. Zhang and H. Su, "CREAM-MAC: cognitive radio-enabled multi-channel mac protocol over dynamic spectrum access networks," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 1, pp. 110 – 123, 2011.

[3] L. Le and E. Hossain, "OSA-MAC:a mac protocol for opportunistic spectrum access in cognitive radio networks." IEEE WCNC, 2008, pp. 1426 – 1430.

[4] A. C.-C. Hsu, D. S. L. Wei, , and C.-C. J. Kuo., "A cognitive mac protocol using statistical channel allocation for wireless ad-hoc networks ,." IEEE WCNC, 2007, pp. 105–110.

[5] C. Cordeiro and K. Challapali, "C-MAC: A cognitive mac protocol for multi-channel wireless networks." IEEE DySpan, 2008, pp. 147–157.

[6] J. So and N. H. Vaidya, "Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver." Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing (MOBIHOC), May 2004.

[7] L. DaSilva and I. Guerreiro, "Sequence-based rendezvous for dynamic spectrum access." IEEE DySpan, 2008, pp. 1 –7.

[8] C.-F. Shih, T. Y. Wu, and W. Liao, "DH-MAC: A dynamic channel hopping MAC protocol for cognitive radio networks." IEEE ICC, 2010, pp. 1–5.

[9] K. Bian, J.-M. Park, and R. Chen, "A quorum-based framework for establishing control channels in dynamic spectrum access networks,." MobiCom 2009, 2009, pp. 25–36.

[10] B. F. Lo, "A survey of common control channel design in cognitive radio networks," *Physical Communication*, vol. 4, no. 1, pp. 26–39, March 2011.

[11] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535 – 547, March 2000.

[12] E. Anderson and R. Weber, "The rendezvous problem on discrete locations," *Journal of Applied Probability*, vol. 27, no. 4, pp. 839–851, 1990.