An Efficient Dynamic Adjusting MAC Protocol for Multichannel Cognitive Wireless Networks

Chih-Shun Hsu, Yuh-Shyan Chen, Chih-En He

Abstract—To enhance the usage of radio spectrum, a wireless network, named as the cognitive wireless network, which allows the unlicensed users to scan and use idle radio spectrum, has attracted a lot of attention recently. Because the radio spectrum has to return to the licensed user whenever the licensed user needs it, the radio spectrum of cognitive wireless networks is a precious resource. Hence, how to avoid collisions and enhance the throughput of the network are important issues for designing MAC protocols of cognitive wireless networks. In this paper, we propose an efficient dynamic adjusting MAC (EDA-MAC) protocol for cognitive wireless networks. EDA-MAC is improved from C-MAC, which assigns each joined host a dedicated beacon slot and thus it has a good potential to avoid contentions and collisions and achieve high throughput. The improvements we made are listed as follows: First, instead of a fixed number of signaling slots of C-MAC, EDA-MAC dynamically adjusts the number of signaling slots according to the number of estimated contenders and thus reduces the number of collisions and shortens the join process. Second, each joined host can inform others its transmission intention by its beacon frame. Since each joined host has a dedicated beacon slot, almost all the beacon frames can be sent without any collision. Third, each communication group contains a leader. The leader is responsible for coordinating the join process, data transmission, transmission rate selection, channel scan, and channel switch of each host in the communication group. With the coordination of the leader, unnecessary contentions and collisions can be avoided and thus enhances the throughput of the network. Simulation results justify the efficiency of the proposed EDA-MAC protocol.

Keywords—cognitive wireless networks, channel scan, channel switch

I. Introduction

The wireless communication spectrum is regulated by the government agency. It permits licensed holders to use the spectrum in particular geographical regions. Since most of the licensed users do not use their allocated spectrum all the time, how to make a good use the idle spectrum has become an important issue.

The cognitive wireless network, which exploits opportunistic spectrum access to employ the spare spectrum, has attracted a lot of attention recently [1],[2]. In a cognitive wireless network, unlicensed users employ the licensed spectrum when licensed users are not using the spectrum and thus improves the usage of the radio spectrum. The design of the medium access control (MAC) protocol would greatly effect the efficiency of a network, especially for a cognitive wireless network which does not have any guaranteed radio resource and should prevent the unlicensed users from interfering licensed users' access to licensed spectrum. There are three approaches to design the MAC protocol of cognitive wireless networks: the random access approach [3],[4], time-slotted approach [5], and the hybrid approach [6],[7]. The first approach is chiefly based on the carrier sense multiple access with collision avoidance (CSMA/CA). The second approach needs time synchronization, while time is divided into slots for both common channel and data channel transmissions. The last approach blends the characters of the other two approaches, such that the control signal mainly occurs over synchronized time slots and data is transmitted without time synchronization. Random access protocols, which adopts CSMA/CA, will cause a lot of contentions and collisions, and thus need to spend more time in exchanging handshake signals and waste radio spectrum of the cognitive wireless network. Therefore, some researches try to make a better use of the spectrum. C-MAC [7] is one of the latest MAC protocols designed for multi-channel cognitive wireless networks. In C-MAC, each channel is divided into several superframes as shown in Fig.1. Only hosts using the same channel need to be synchronized; hosts using different channels need not to be synchronized. Therefore, it can avoid wasting the radio spectrum during the Ad hoc Traffic Indication Messages (ATIM) window and thus improves the Multi-channel MAC (MMAC) protocol [4]. Besides, each joined host is assigned with a dedicated beacon slot such that each joined host can use its dedicated beacon slot to transmit beacon frames to its neighbors without any contention and collision. The major drawbacks of C-MAC are that it does not make a good use of the dedicated beacon slot to avoid collisions of data transmissions and enhance the throughput, and it has only a fixed number of signaling slots which may cause a long join process.

To improve C-MAC, we propose an efficient dynamic adjusting MAC (EDA-MAC) protocol for multi-channel cognitive wireless networks. The improvements we made are listed as follows: First, instead of a fixed number of signaling slots of C-MAC, EDA-MAC dynamically adjusts the number of signaling slots according to the number of estimated contenders and thus reduces the number of collisions and shortens the join process. With a faster join process, the unlicensed user can join a communication group efficiently and can start its transmission earlier and thus improves the throughput of the network. Second, each joined host can inform others its transmission intention by its beacon frame. Since each joined host has a dedicated beacon slot, almost all the beacon frames can be sent without any collision. By collecting all the information

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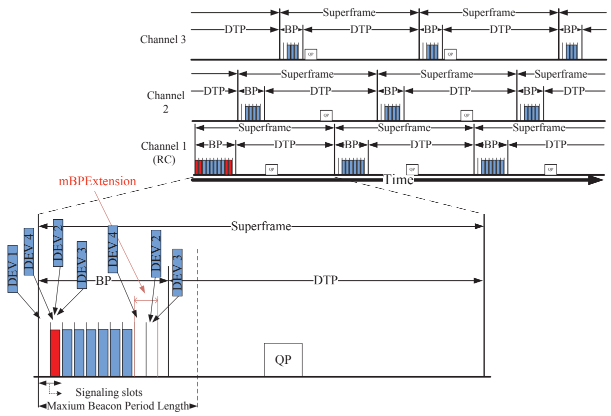


Fig. 1. C-MAC architecture

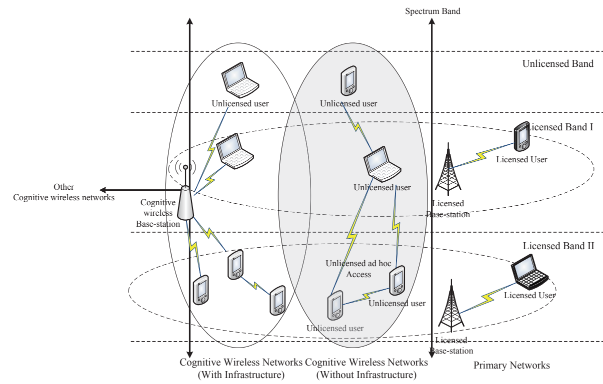


Fig. 2. Cognitive wireless network architecture

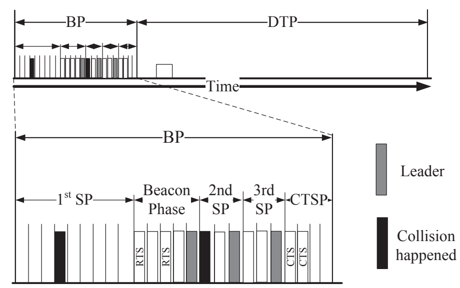


Fig. 3. The structure of a Beacon Period

of the beacon frames, contention-free transmissions can be made by proper scheduling in EDA-MAC. Third, the first host that scans the spectrum and forms the communication group would become the leader. The leader is responsible for coordinating the join process, data transmission, transmission rate selection, channel scan, and channel switch of each host in the communication group. With the coordination of the leader, proper transmission rate can be selected, unnecessary contentions and collisions can be avoided and thus enhances the throughput of the network. Simulation results shows that the proposed EDA-MAC protocol outperforms C-MAC in terms of average join time and throughput.

The rest of the paper is organized as follows: Section 2 presents the assumptions and system model of the paper. Section 3 shows the proposed EDA-MAC protocol. Simulation and performance evaluation are demonstrated in section 4. Section 5 concludes the paper.

II. System model and assumptions

The architecture of cognitive wireless networks is shown in Fig. 2. In a cognitive wireless networks, an unlicensed user can scan and use idle spectrum no matter they belong to licensed or unlicensed bands. The cognitive wireless network can be either with or without infrastructure. In this paper, we focus on an cognitive wireless network without infrastructure which is based on unlicensed ad hoc access. Before an unlicensed user starts its communications, it should join a communication group first.

Several communication groups may coexist in the cognitive wireless networks. A host and its neighbors can form a communication group. To avoid interference, neighboring groups can not use the same channel. Therefore, before using any channel, a host should listen the channel for a superframe. A host should broadcast the channel usages of its group in its beacon frame. A host that has joined more than one communication groups may play as the bridge for intergroup communications.

III. EDA-MAC

The proposed EDA-MAC is shown in this section. The initialization mechanism is shown first. The data transmission mechanism is shown next, followed by the channel switching and recovery mechanisms. Finally, the maintenance mechanism is presented.

A. Initialization mechanism

Initially, any unlicensed user, who wants to use the idle spectrum (licensed or unlicensed), should scan the spectrum first. If it has detected an existing communication group, it may follow the join process to join the communication group or it may form a new communication group. The join process would be described later. The first host that scans the spectrum and forms the communication group would become the leader. The channel chosen to form the communication group is named as the rendezvous channel. Any unlicensed users intend to join the communication group should listen to the rendezvous channel for a superframe to gather necessary information announced by the leader.

Similar to C-MAC, the proposed EDA-MAC also divides a channel into consecutive superframes. Each superframe contains a beacon period (BP) and a data transmission period (DTP). Each BP contains one to several signaling phases (SP), a beacon phase, and a CTS phase as shown in Fig. 3. The length of BP is variable but it cannot exceed the maximum beacon period length. As the signaling phase becomes longer, BP also becomes longer and DTP will become shorter because the length of superframe is fixed. Each signaling phase contains several signaling slots. During the signaling phase, the host which intends to join the communication group will contend to transmit a signal in one of the signaling slots. The host which successfully transmit its signal without any collision will be assigned with a dedicated beacon slot by the leader and then it can communicate with other hosts in the communication group.

To avoid collision and accelerate the join process, we propose a dynamic adjusting join mechanism. When a new communication group is formed, since there is only one host in the communication group, the signaling phase is maximized while the beacon phase contains only the leader's dedicated beacon slot. As some unlicensed users has detected the rendezvous channel and intend to join the communication group, the leader will count the number of successful joined hosts (denoted as SUC) and the number of collisions (denoted as COL), and then it can estimated the number of contenders (denoted as N_e) of current superframe according to the number of signaling slots (denoted as m), successful joined hosts, and collisions and calculates the number of possible contenders of next superframe (denoted as N_c) as $N_c = N_e - SUC + \lambda$, where λ is the average arrival rate of the join hosts of next superframe. The number of signaling slots of next superframe (denoted as N_s) can then be set according to N_c. After the signaling phase, the leader will announce the dedicated beacon slots of each newly joined hosts and N_s by its beacon frame so that each newly joined hosts can start to use its dedicated beacon slots to start its communication and those who fails to join or intends to join can randomly pick a signaling slot according to N_s during the signaling phase of next superframe.

How to estimate the number of contenders according to the number of signaling slots, successful joined hosts and collisions is shown as follows:

First, calculates the expected value of successful joined hosts and collisions with all the possible numbers of contenders and signaling slots. The recursive functions to calculate the expected value of successful joined hosts (denoted as $ES(n,m)$) and collisions (denoted as $EC(n,m)$) with n contenders and m signaling slots are shown as follows that have been proposed in [8]:

$ES(n,m) = pb(n,m,0)ES(n,m-1) + pb(n,m,1)(ES(n-1,m-1)+1) + \sum_{k=2}^{n} pb(n,m,k)ES(n-k,m-1)$, where $ES(0,0)=0$, $ES(1,m)=1$, $m>0$, and $ES(n,1)=0$, $n>1$.

$EC(n,m) = pb(n,m,0)EC(n,m-1) + pb(n,m,1)EC(n-1,m-1) + \sum_{k=2}^{n} pb(n,m,k)(EC(n-k,m-1)+1)$, where $EC(0,0)=0$, $EC(1,m)=0$, $m>0$, and $EC(n,1)=1$, $n>1$.

$pb(n,m,k) = C_k^n (\frac{1}{m})^k (\frac{m-1}{m})^{n-k}$ is the probability that k hosts send their signals in the m-th time slot and the other $n-k$ hosts send their signals in the first $(m-1)$ time slots, where $0 \le k \le n$, $C_k^n = \frac{n!}{(n-k)!k!}$. Dynamic programming is used to solve $ES(n,m)$ and $EC(n,m)$.

Second, look up the tables generated by $ES(n,m)$ and $EC(n,m)$ to find the number of contenders according to the number of signaling slots, successful joined hosts and collisions.

Third, estimate the number of contenders as $N_e = \max(N_{suc}, N_{col}, N_{low})$, where N_{suc} and N_{col} are the numbers of contenders found according to the number of successful joined hosts and collisions, respectively, and $N_{low} = SUC + COL \times 2$ is the lower bound of the estimated number of contenders.

For example, if the number of signaling slots is 3 and there are 2 collisions and 1 successful joined host. The lower bound of the estimated number of contenders is $N_{low} = SUC + COL \times 2 = 2 + 2 = 4$. By looking up Tables I and II, we can find that N_{suc} and N_{col} are 5 and 6, respectively. Therefore, the number of estimated contenders is $N_e = \max(N_{suc}, N_{col}, N_{low}) = \max(5,6,4) = 6$. If $\lambda = 2$, then the number of possible contenders of next superframe is $N_c = N_e - SUC + \lambda = 6 - 1 + 2 = 7$. The number of signaling slots of next superframe N_s is set according to N_e and the expected successful rate. If the expected successful rate is 60%, then there should be $7 \times 60\% = 4.2$ successful hosts. By checking Table I, N_s should be set as 12.

TABLE I
THE EXPECTED VALUE OF SUCCESSFUL JOINED HOSTS

$N_e \backslash m$	2	3	4	$\cdots$	11	**12**	13
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
4	0.5	1.1852	1.6875	$\cdots$	3.0053	3.081	3.1461
5	0.3125	0.9877	1.582	$\cdots$	3.4151	3.5303	3.6301
6	0.1875	0.7901	1.4238	$\cdots$	3.7255	3.8834	4.0211
7	0.1094	0.6145	1.2459	$\cdots$	3.9513	**4.153**	4.3304

TABLE II
THE EXPECTED VALUE OF COLLISIONS

$N_e \backslash m$	2	3	4	$\cdots$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
5	1.625	1.6173	1.4688	$\cdots$
6	1.7813	1.9465	1.8643	$\cdots$
7	1.875	2.21	2.2202	$\cdots$

When there are some collisions occurred in the signaling phase and there remains some available time in the beacon period, we can add the second or even the third signaling phases at the end of the beacon phase so as to further accelerate the join process as shown in Fig. 3.

B. Data Transmission Mechanism

In this subsection, the rate selection protocol is described first, followed by the transmission scheduling protocol.

1) Rate Selection Protocol: The goal of rate selection is to adopt the proper transmission rate so as to achieve higher throughput. Our rate selection protocol is similar to the one proposed in [9]. The RTS and CTS control frames have been changed to encode a 4 bits rate subfield and a 12 bits length subfield, to replace the 16 bits duration field in the frames However, to fit the frame structure of our protocol and to avoid contentions and collisions, we make some modifications as follows: The leader is in a promiscuous mode. The RTS frame is transmitted in the dedicated beacon slot of the sender. After hearing the RTS sent by the sender, the leader will schedule the reply sequence of the receiver. Each receiver reply a CTS during the CTS phase according to the reply sequence and thus it can complete the rate selection process without any contention and collision as shown in Fig. 3.

2) Transmission Scheduling Protocol: The main goal of data transmission scheduling is to avoid collisions and contentions. After hearing the CTS send by the receiver, the leader will assign each sender a transmission sequence according to the requirement as shown in Fig. 4. For example, if fairness is the major concern, the sender with least transmissions can transmit first. If the data transmission period is not long enough to contain all the transmissions, the leader can ask some senders and receivers to switch to other channels.

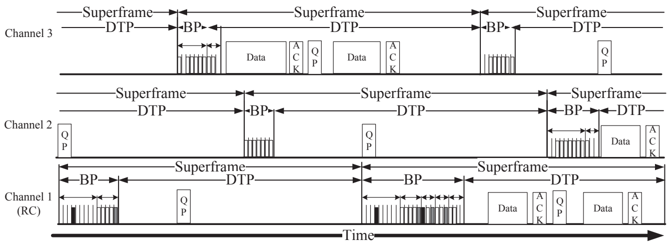


Fig. 4. Multi-channel superframe structure

C. Multi-channel Switching Mechanism

The goal of the multi-channel switching mechanism is to achieve load balance in multi-channel structure. The leader manages channel switching according the traffic load of each channel. The leader broadcast the channel switching message at the end of the beacon period. The frame structure of other channels is similar to the structure of RC. When a host needs to switch to other channels, it follows the join process to join and use the channel and follows the data transmission mechanism to communicate with other hosts. The first host that join and use the channel will become the leader of the channel. To maintain synchronization, the hosts, which has switched to other channels, need to switch back to RC during the RC leader's dedicated beacon slot periodically.

D. Recovery Mechanism

The goal of designing the recovery mechanism is to detect the interference from licensed user and rescue the communication group of unlicensed users. There is a quite period (QP) during each data transmission period for unlicensed users to detect the status of the licensed users as shown in Fig. 4. The recovery mechanism uses backup channels to recover when the rendezvous channel interferes with licensed users' signals. The channel with better quality will be chosen as the backup channels. If non-rendezvous channel interferes with licensed users, then the host return to rendezvous channel to join the communication group again.

E. Maintenance mechanism

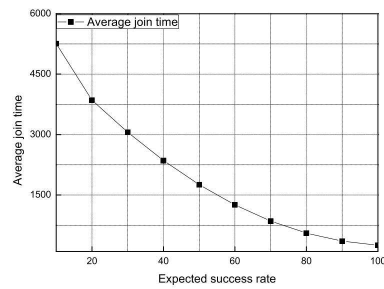
To balance the load and power consumption of each host in the same group, each host should play as the leader in turn. Each host serves as the leader periodically in an order based on its join sequence in the group. When the remaining power of a host is lower than a certain threshold, it will no longer serve as the leader. When a host is going to leave the group, it will inform the leader in its dedicated beacon slot. If the leader can no longer hear from its member, it should take back this member's dedicated beacon slot. On the other hand, if a host can no longer hear from its leader, it can join other groups or form a new group.

IV. Performance Evaluation

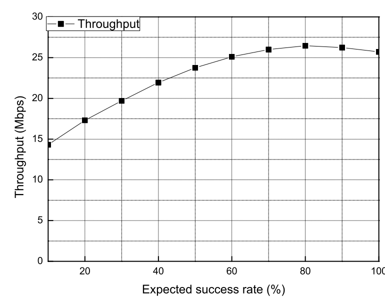
To evaluate the performance of the proposed EDA-MAC, we compare its performance with that of C-MAC. The simulation parameters is shown in Table III. Why the expected success rate is set as 80% will be discussed later.

TABLE III
SIMULATION PARAMETERS

Description	Value
Simulation tool	$Ns-2$
Simulation area	50m $\times$ 50m
Communication range	25m
Simulation Duration	10 sec
Superframe length	100ms
Maximum beacon period length	30ms
Transmission rate	36 $\sim$ 54Mbps
Traffic load	0 $\sim$ 10M bytes/sec
Expected Success Rate	80%



(a)



(b)

Fig. 5. Expected successful rate vs. (a) average join time (ms) and (b) throughput

The performance metrics observed in our simulations are average join time and throughput.

A. Expected Successful Rate

Fig. 5 shows the impact of expected successful rate to average join time and throughput. As the expected successful rate increases, the number of signaling slots also increases and the average join time decreases. When the expected successful rate exceeds 80%, the beacon period will become too long and the data transfer period will become too short to contains enough pairs of communications and thus decreases the throughput. Therefore, in the following simulations, we will set the expected successful rate as 80%.

B. Average join time

Fig. 6 shows the impact of the arrival rate of unlicensed users to average join time. The average join time of the

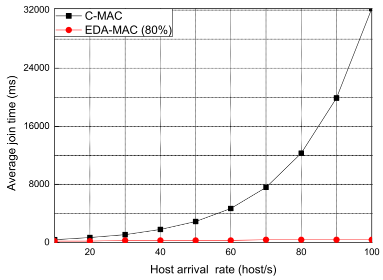


Fig. 6. Average join time vs. arrival rate of unlicensed users

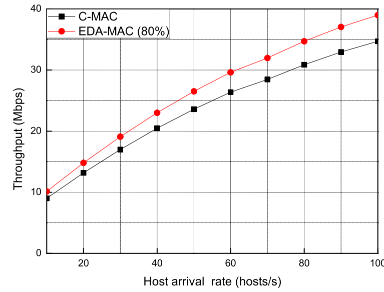
proposed EDA-MAC is much shorter than that of C-MAC especially when the arrival rate of unlicensed users increases. Since the proposed EDA-MAC can dynamically adjust the number of signaling slots according to the number of estimated contenders, it is more scalable than C-MAC.

C. Throughput

Fig. 7 shows the impact of available channels, arrival rate of unlicensed users, and traffic load to throughput. As available channels, arrival rate of unlicensed users, and traffic load increases, the throughput also increases. The proposed EDA-MAC has higher throughput than C-MAC and declined slower than C-MAC because our protocol can let unlicensed hosts join fast and can avoid contentions and collisions and thus can achieve higher throughput even when the traffic load is high.

V. Conclusion

In this paper, we have proposed an efficient dynamic adjusting MAC (EDA-MAC) protocol for multi-channel cognitive wireless networks. The proposed EDA-MAC can dynamically adjust the number of signaling slots according to the number of estimated contenders and thus reduces the number of collisions and shortens the join process. Besides, our protocol make a better use of the dedicated beacon slot and let the leader of the communication group coordinate the join process, data transmission, transmission rate selection, channel scan, and channel switch of each host in the communication group. With the coordination of the leader, unnecessary contentions and collisions can be avoided and thus enhances the throughput of the network. Simulation results have shown that the proposed EDA-MAC protocol outperforms C-MAC in terms of average join time and throughput.



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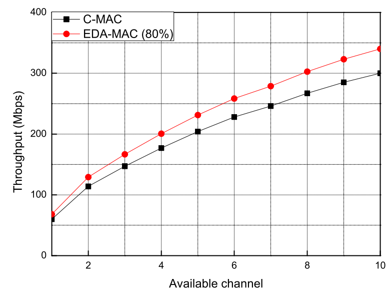

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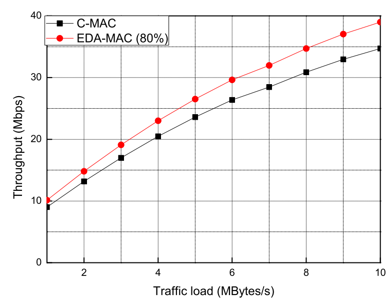

(c)

Fig. 7. Throughput vs. (a) available channels, (b) arrival rate of unlicensed users and (c)traffic load

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