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Efficient Cognitive MAC Protocol under WLAN Coexistence

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Abstract. In the past few decades, with the development of mobile communication services in Wireless Local Area Networks (WLANs), the demand for available wireless spectrum has rapidly increased. In recent research, the traditional fixed spectrum assignment policy cannot use spectrum effectively in WLANs. A cognitive radio network (CRN) allows providing unlicensed users, called Secondary User (SU), with opportunistic access to the licensed bands without interfering with the existing users. In this paper, we propose a CRN MAC to use the spectrum of WLANs much more efficiently by allowing SUs to coexist with WLAN users. The proposed MAC aims to not only allocate an unused channel with better transmission quality for SUs, but also to guarantee the performance declination of the WLAN users below a pre-defined threshold. The latter is validated by a mathematical analysis based on Markov chain models. Further, simulation results show that the proposed CRN MAC is superior to a recent work in avoiding interference to the WLAN users, improving the throughput of spectrum, and inducing less overhead.

Keywords: cognitive radio, MAC protocol, dynamic spectrum access

1 Introduction

Radio spectrum is a kind of limited natural resource and its use is licensed and assigned by governmental agencies. According to the statistics of the Federal Communications Commission (FCC) in [1], temporal and geographical variations in the utilization of the assigned spectrum range are from 15% to 85%. The unused spectrum is referred to as spectrum hole or white space [2].

The radio spectrum is divided into frequency bands, and each band is further divided into frequency channels. These frequency bands are assigned to particular system users called licensed users, and they are called licensed bands. According to the statistics by FCC, more than 90 of licensed bands are unused at any given time, since the licensed users do not utilize the entire allocation of the licensed bands. On the other hand, a small number of the frequency bands not assigned to particular systems are called unlicensed bands.

The limited available radio spectrum and the inefficiency in spectrum usage necessitate a new communication paradigm to exploit the existing spectrum dynamically. The cognitive radio network (CRN) is one of the most efficient paradigms for allowing unlicensed users with opportunistic access to the licensed bands without interfering with the existing licensed and unlicensed users. In a CRN, a licensed user is called Primary User (PU) and an unlicensed user is called Secondary User (SU). The spectrum utilization is improved by allowing SUs to use the unused licensed bands. The above successful operations in a SU depend on a medium access control (MAC) protocol, which can sense and allocate the idle channels without causing interference to PUs and release these channels when PU activity is detected.

CRN *is* divided *into two categories,* licensed band CRN and unlicensed band CRN, which use the licensed bands and the unlicensed parts of radio frequency spectrum, respectively [3]. In a licensed band CRN, a SU can sense idle channels, select an available channel, coordinate to the channel with other SUs,

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and vacate the channel when a PU needs to use the channel [4-5].

A Wireless Local Area Network (WLAN), which uses the unlicensed 2.4GHz and 5GHz bands, is one of most popular wireless networks. The SUs selecting the same frequency bands of the WLAN, should avoid harmful interference to the WLAN traffic flows. In a multi-channel wireless ad-hoc network, a Dynamic frequency selection (DFS) approach is adapted for sensing and allocating the channels [6].

Recently, several CRN MAC protocols [7-19] are proposed. However, the above proposed protocols are likely to induce a problem of improper channel allocation while allocating a channel for a transmission between a sender-receiver pair. Only considering the channel utilization status of the sender is the reason to induce the problem. The problem of improper channel allocation will be elaborated in the next section.

In this paper, we propose a Mac which is different those proposed in [7-19] by considering the following two problems: (1) to solve the problem of improper channel allocation, and (2) to coexist SUs with WLAN users. For the first issue, the proposed MAC extends the RTS-CTS-DATA-ACK handshake mechanism of IEEE 802.11 MAC for obtaining the utilization status of all available channels between the sender and the receiver. By the aid of the handshake extension, it can avoid the above problem, and then allocates an unused channel not only with better transmission quality but also without causing harmful interference to PUs.

For the second issue, the proposed MAC contains an active traffic control mechanism for protecting the flows transmitted by WLAN users from the interference induced by CRN users, i.e., SUs. The proposed mechanism uses the mechanism of Carrier Sense Multiple Access (CSMA) based on a listen-before-talk operation for sensing an idle channel and transmitting data packets. It is used by a SU for selecting a channel or changing to another channel in order to maintain the transmission quality of the flows transmitted by WLAN users.

Extensive simulations are carried out and an analytical model is proposed for validating the performance of the two proposed mechanisms. Simulation results show that our proposed CRN MAC has 10.2% and 7.6% improvement in WLAN users' and SU's receiving rates bytes over the existing CRN MAC, respectively. On the other hand, it reduces the control overhead rate from 9.15% to 4.7%. Further, the analytical results show that the second mechanism can bound the transmission performance declination of the WLAN users well below a predefined threshold when CRNs coexist with WLANs. Simulation results further show that the transmission performance of the WLAN users only decline to 99.2%, while the threshold is set to 0.99.

The remainder of this paper is organized as follows: Section 2 discusses the related works of previous CRN MAC research. Section 3 describes the proposed MAC protocol. The simulations and the analytical model are demonstrated in Section 4. Finally, a conclusion is given in section 5.

2 Related Works and Problems

In this section, several CRN MAC protocols [7-19] are first reviewed. Then, the problem of improper channel allocation is explained with an illustrative example.

In [7], a cognitive MAC protocol for multichannel wireless networks is proposed for coordinating nodes in multi-channel reservation. However, it is less concern on the protection of PU's traffic flow. In [8], the authors propose an energy-efficient distributed multichannel MAC protocol based on the assumption that PUs and SUs share the same slotted transmission structure. In [9], the authors propose a MAC protocol on a wireless mesh network for the operations of sensing and allocating the channels. In [10], the authors discuss the hardware limitations of practical CRNs, including sensing overhead, period of sensing channels, and maximum spectrum bandwidth that SU can use. A MAC protocol is proposed for allowing a SU to use some discontinuous frequency bands as a single channel.

In [11], the authors propose a CRN MAC protocol, which uses a channel access model, named as Partially Observation Markov decision process (POMDP), for allocating the channels of SUs. In [12], the throughput of both PUs and SUs is calculated by considering channel capture effect. In [13], the authors develop an analytical model of using overlay operation mode in SUs, and calculate the saturation throughput of the mode. In [14], the authors have proposed a MAC protocol for both single-channel and multiple-channel scenarios based on the RTS and CTS mechanisms along with the asynchronous spectrum sensing. In [15], an adaptive spectrum sharing mechanism for code division multiple access based MAC in the uplink communication over CRN is proposed.

In [16], the authors focus on cooperative resource allocation in multi-carrier CRNs by adopting the two-stage harvest-then-transmit protocol where the wireless power transfer for the PU is executed first and then the information transfer for the PU takes place. In [17], the authors study the problem of network coding-based multicast in mobile cognitive radio ad hoc networks considering both channel uncertainty and node mobility by utilizing discrete-time Markov chains to model the channel availability and node mobility.

In [18], the authors describe the design and implementation of an extensible and flexible self-optimization framework for cognitive home networks. They utilize the cognitive resource manager as an architecture of the individual agents to allow achieving high system flexibility while providing structural constraints to ensure robustness. In [19], the authors propose a fair multi-channel assignment scheme for distributed CRNs by designing a new MAC framework for sensing and access contention resolution. The objective is to find a channel assignment with maximal fairness index for all SUs.

The previous CRN MACs [7-19] may suffer from the problem of improper channel allocation, which is induced by only considering the channel utilization status of the sender. Refer to Fig. 1, a sender and a receiver are denoted as node A and node B, respectively. An illustrative example is shown for the problem. Node A and node B have different channel availability and utilization information sets. The channel information are describe as (x, y), in which x denotes the available channel number and y denotes the channel utilization, respectively.

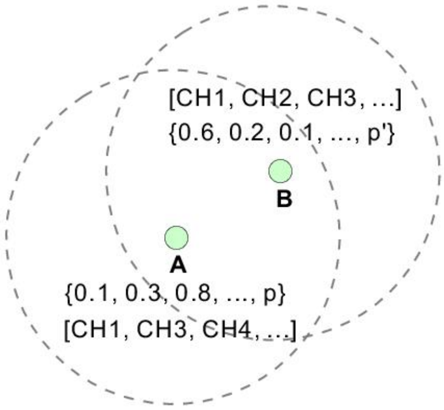


Fig. 1. An example of inconsistent status of channel utilization between a sender-receiver pair

Suppose that node A has the channel information set of {(1, 0.1), (3, 0.3), (4, 0.8)} and node B has the one of {(1, 0.6), (2, 0.2), (3, 0.1)}. Obviously, channel 2 is available for node B but it is busy for node A. Consequently, channel 2 is not an available channel of link A-B. On the other hand, if a channel allocation mechanism only considers the utilization status of all channels of the sender, channel 1 will be selected for the link, since its channel utilization is smallest among the all channels of node A. However, its channel utilization is largest among the all channels of node B, and node B may suffer from serious interference. In the example of Fig. 1, a better choice is to select channel 3 for the link from node A to node B.

3 Protocol

In this section, we propose a CRN MAC based on the following assumptions: (1) there are n data channels available in a CRN, and they are orthogonal (interference-free to each other). A predefined channel is used for transmitting control packets, and it is called common control channel. The others are used for transmitting data packets. (2) The CRN coexists with WLAN in an overlay model, which only allows the SUs and the WLAN users to use the channels exclusively, i.e., a channel can be used only by a user (a SU or WLAN user) in one time. The assumption is also adopted in the works [8-11]. (3) The common control channel is only available to all SUs, whereas the rest are available to all users. (4) A PHY layer at a SU is able to gather the status of these channels periodically. (5) Each SU has two half-duplex transceivers; where one transceiver is used for listening/accessing the common control channel and the other is used for transmitting data packets on the other channels.

Two mechanisms in the proposed CRN MAC are proposed to solve the following two issues: (1) to solve problem of improper channel allocation, and (2) to coexist SUs with WLAN users. In the standard 4-way handshake mechanism (i.e., RTS-CTS-DATA-ACK) of IEEE 802.11 MAC for a sender-receiver pair, the sender sends an RTS packet to the receiver, and the receiver replies a CTS packet if it receives the RTS packet. Then, the sender sends a DATA packet to the receiver, and the receiver replies an ACK packet.

In the proposed two mechanisms, the RTS-CTS-DATA-ACK handshake mechanism is enhanced by adding extra confirm RTS (denoted as CRTS) control packet, and by transmitting *m* DATA/ACK (denoted as *m*DATA/*m*ACK) packets where *m* is a variable and will be discussed later. The handshake mechanism sequence of IEEE 802.11 MAC will be modified as RTS-CTS-CRTS-*m*DATA-*m*ACK.

For the first issue, i.e., to solve the problem of improper channel allocation, the first mechanism (named as RTS-CTS-CRTS handshake mechanism) is proposed for channel selection and reservation by using RTS and CTS packets to exchange the channel information between the sender and the receiver. The sender transmits the RTS and CTS packets by using the common control channel to obtain the channel information of both it and the receiver. Hence, the problem of improper channel allocation can be solved. Further, a channel with better transmission quality can be selected.

For the second issue, i.e., to coexist SUs with WLAN users, the second mechanism (named as active traffic control mechanism), is proposed to control the amounts of DATA and ACK packets in a RTS-CTS-CRTS-*m*DATA-*m*ACK operation. In order to avoid the performance declination of WLAN users, the active traffic control mechanism aims to determine the variable *m* for guaranteeing that the performance declination of WLAN users is below than a pre-defined threshold.

The two proposed mechanisms are presented in Section 3.1 and Section 3.2, respectively. Afterward, the detail protocol description, data structure, and state transition diagram will be introduced in Section 3.3.

3.1 RTS-CTS-CRTS-*m*DATA-*m*ACK Handshake Mechanism

Suppose that there are n data channels available in a CRN, and let $ch_{i,j}$ be the status of the jth channel at user i, where $1 \le j \le n$. We use $ch_{i,j} = 0$ and $ch_{i,j} = 1$ to denote that the channel is idle and busy, respectively. Let $u_{i,j}$ be the utilization of the channel, and $m_{i,j}$ be the determined variable for the amounts of DATA and ACK packets in a RTS-CTS-CRTS-*m*DATA-*m*ACK operation. The variable $m_{i,j}$ is determined by the active traffic control mechanism which will be presented in Section 3.2. On the other hand, the variables $ch_{i,j}$ and $u_{i,j}$ are provided by the physical layer periodically, and the methods of obtaining the variables will be presented in Section 3.3.

The RTS-CTS-CRTS-*m*DATA-*m*ACK operation for a SU sender-receiver pair, say v_s and v_r, is illustrated in Fig. 2. For easy reference, Table 1 lists all variables used in this section. The sender v_s sends the RTS packet to the receiver v_r by carrying the utilization status of its available channels, i.e., every pair of $(ch_{v_s,j}, m_{v_s,j})$, where $ch_{v_s,j} = 0$ and $1 \le j \le n$. Once v_r receives the RTS packet, it determines a data channel, say x ($1 \le x \le n$), with the smallest channel utilization between v_s and v_r by the equation

$$x = \arg \max_{x \in \{ j | ch_{v_s,j}=0,\ j | ch_{v_r,j}=0, 1 \le j \le n\}} (\min\{m_{v_s,x}, m_{v_r,x}\}).$$

Table 1. Variables used in Section 3

Parameters	Meaning	Value
n	Amount of data channels	
$ch_{i,j}$	Availability of channel j to SU i	$ch_{i,j} \in \{0, 1\}$
$u_{i,j}$	PU's utilization of user i on channel j	$0 \leqq u_{i,j} \leqq 1$
$m_{i,j}$	Amount of data packets of user i on channel j	$m_{i,j} \geqq 0$
l_ACK	Length of ACK packet	
threshold	Pre-defined traffic decline threshold to PU	0 < *threshold* < 1
l_DATA	Length of DATA packet	
α	A parameter for guaranteeing the performance of WLAN users	$0 < \alpha \leqq 1$

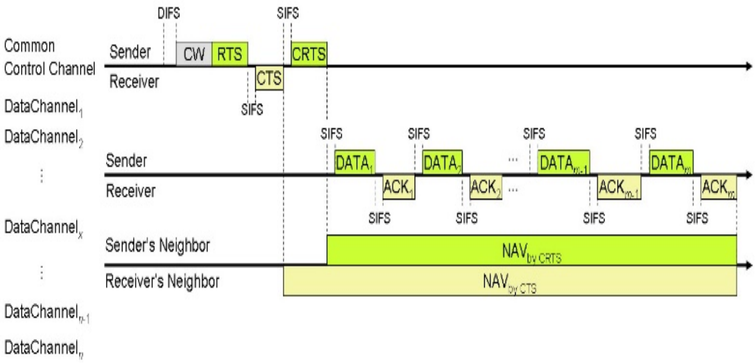


Fig. 2. RTS-CTS-CRTS-*m*DATA-*m*ACK operation

And, the determined channel x will be used for the mDATA-mACK operation. In order to solve the problem of improper channel allocation when the m DATA packets and m ACK packets are transmitted on x, m is set to $\min\{m_{v_s,x}, m_{v_r,x}\}$.

Then, v_r returns x and m to v_s by the CTS packet. Once one of its neighboring SUs receives the CTS packet, it sets the NAV time equal to

$$t_{\text{SIFS}} + t_{\text{CRTS}} + m\times(2\times t_{\text{SIFS}} + t_{\text{DATA}} + t_{\text{ACK}})$$

where t_{SIFS}, t_{CRTS}, t_{DATA} and t_{ACK} are the time duration of SIFS, CRTS, data packet and ACK, respectively. During the period of the NAV time, its neighboring SUs are blocked (i.e., forbidden to send packets). After receiving the CTS packet, v_s sends the CRTS packet to inform its neighboring SUs with the same purpose. Differently, the neighboring SUs set the NAV time equal to

$$t_{\text{SIFS}} + m\times(2\times t_{\text{SIFS}} + t_{\text{DATA}} + t_{\text{ACK}})$$

Once RTS-CTS-CRTS handshake operation is finished, v_s transmits the data packets on the channel x after SIFS period. While receiving each DATA packet, v_r returns an ACK packet to v_s. After all m packets are sent or being collided with other user, v_s and v_r re-start the RTS-CTS-CRTS handshake again to select a new data channel if the data packet queue is not empty.

3.2 Active Traffic Control Mechanism

In this section, the active traffic control mechanism is proposed to determine the amount of DATA packets for the RTS-CTS-CRTS-mDATA-mACK operation, i.e., to determine the value of m. If a SU occupies the data channel determined in the first proposed mechanism by continuously transmitting data packets on the determined channel for a long period, the performance of the WLAN users will decline since the WLAN users cannot use the determined channel during the period. In order to avoid the performance declination of these WLAN users, the proposed traffic control mechanism transmits only m data packets on the selected data channel in each RTS-CTS-CRTS-mDATA-mACK operation. Then, it vacates the channel, and starts another operation for selecting a new data channel and determining a new value of m.

The value of m is determined according to the current channel utilization of a SU v_i on channel j, i.e., $u_{i,j}$. A channel with smaller channel utilization can result in a larger value of m. However, a larger m also causes the performance declination of WLAN users using this channel. The proposed active traffic control mechanism tries to determine an m as large as possible, but that the performance declination of WLAN users is below than a pre-defined threshold, say *threshold*.

When v_i tries to transmit a packet using the data channel j with the current channel utilization $u_{i,j}$, the channel j will be occupied with the probability of $u_{i,j}$ in the coming time. In other words, none of WLAN users' flows will be transmitted on j with the probability of $(1-u_{i,j})$. Similarly, if v_i transmits k packets in succession, the probability of without other flows transmitted on j will be $(1-u_{i,j})^k$. Apparently, larger k is preferred. However, the performance of the WLAN users will decline since the channel is occupied by v_i for a long period in transmitting the k packets in succession.

In a RTS-CTS-CRTS-mDATA-mACK operation, v_i transmits m DATA packets and m ACK packets in succession on *j*, and transmits the three control packets (i.e., RTS, CTS, CRTS) on the control channel, i.e., when v_i tries to use the data channel *j*, it needs to determine a maximal *k* but guarantee $(1-u_{i,j})^k > threshold$. Note that *k* is the aggregate of the amounts of DATA packets and ACK packets. For example in the instance of *threshold* = 0.6 and $u_{i,j}$ = 0.2, the maximal *k* should be 2 since if $k > 2$ then $(1\text{-}0.2)^k < 0.6$. In this instance, SU v_i is only allowed to transmit 2 data packets in this RTS-CTS-CRTS-*m*DATA-*m*ACK operation on channel *j*. Once v_i determine the value of *k*, it can obtain the value of *m* by Equation (1).

$$m = \left\lfloor a \times \left\lfloor k \times (1 - \frac{l\_ACK}{l\_DATA}) \right\rfloor \right\rfloor \quad \textbf{(1)}$$

Where l_ACK and l_DATA are the lengths of ACK and DATA, respectively, and *α* is a weighted factor. In Equation (1), $\frac{l\_ACK}{l\_DATA}$ represents the ratio of control overhead induced from the ACK packets to the DATA packets. It implies that the ratio of really transmitting DATA packets while consuming one-unit bandwidth of *j* is $1-\frac{l\_ACK}{l\_DATA}$. We multiply $\left\lfloor k \times (1-\frac{l\_ACK}{l\_DATA}) \right\rfloor$ by *α* for providing a certain level of guaranteeing the performance of WLAN users. How to set the value of *α* will be presented in Section 4.1.

3.3 Implementation

In this section, we introduce the methods of obtaining the information which is necessary to the two proposed mechanisms. The information includes $u_{i,j}$, $ch_{i,j}$, *l_ACK*, *l_DATA, rate*$_j$ and *threshold*, where $rate_j$ is the data rate for transmitting packets on channel *j*. The two variables $u_{i,j}$ and $ch_{i,j}$ can be auto-correlated by one of its two half-duplex transceivers at a SU. Whenever the SU is idle, this transceiver is used to listen to each data channel periodically, and the other transceiver is used to listen to the control channel.

Monitoring the amount of idle time of the channel *j*, *i_time*, during every time period, *p_time*, yields an estimate of $u_{i,j}$ as $(1-\frac{i_{time}}{p_{time}})$. The estimated $u_{i,j}$ must be modified by a linear historical prediction model for obtaining a smooth prediction value as $u_{i,j} = wu_{i,j} + (1-w)\hat{u}_{i,j}$, where $\hat{u}_{i,j}$ is the average experienced utilization of the past, and *w* is a weighting factor of historical data.

The MAC formats of RTS, CTS, CRTS, DATA and ACK are defined in Fig. 3, where a RTS-CTS-CRTS-*m*DATA-*m*ACK operation is executed between sender v_s and receiver v_r on channel *j*. As shown in Fig. 4, the packet sizes of RTS, CTS, CRTS and ACK are fixed. Then, we can obtain the packet size (i.e., *l_ACK*) of ACK as 14 bytes. On the other hand, the selection of the packet size of DATA is a complicated issue because it may be affected by some factors such as the collision probability of packets. For simplicity, its size (i.e., *l_DATA*) is fixed to 1000 bytes in this paper. Thus, one future work is to dynamically adjusting the size.

Since higher data rates can result in smaller transmission delays, $rate_j$ is set to the highest rate of channel *j*. For example, the highest rate for 802.11b is 11 Mbps. In order to protect the performance of WLAN users, the value of *threshold* is set based on the characteristics of applications executed on these users. For example, the tolerated packet loss rate of audio quality for a VoIP application with G.711 codec is 3% to 5% [20]. In this case, *threshold* should be set greater than 0.97.

As shown in Fig. 4, each SU v_i keeps a (n + 1)-entry channel state table in order to maintain all the channel information, i.e., $ch_{i,j}$, $u_{i,j}$; *l_ACK*, *l_DATA, threshold* and $rate_j$ for the control channel and the all data channels. On the other hand, the additional variables $nav\_time_{i,0}$ and $nav\_time_{i,j}$ (where $1 \le j \le n$) in Fig. 4 are the NAV times of the control channel and the data channel *j* in v_i, respectively. They are used for reducing the possibility of collisions with other users. Once a channel has an NAV time countdown to zero, v_i can transmit packets on it. Recall that v_i can estimate these variables by the method of Section 3.1, and exchange them with its neighboring SUs via control packets (i.e., CTS and CRTS) as shown in Fig. 3.

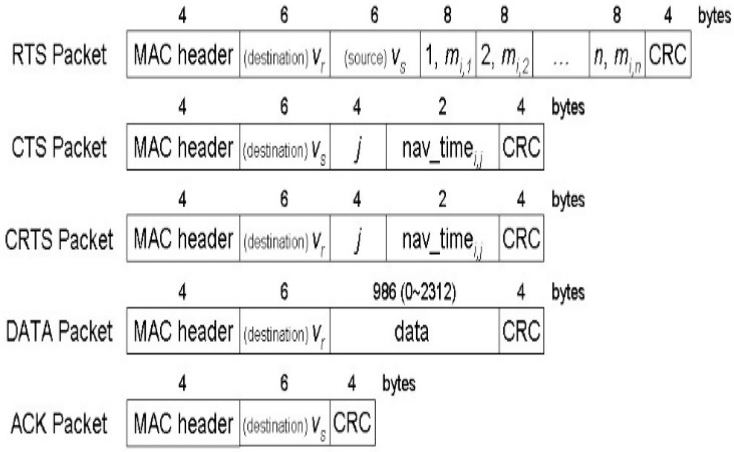


Fig. 3. MAC formats of RTS/CTS/CRTS/DATA/ACK

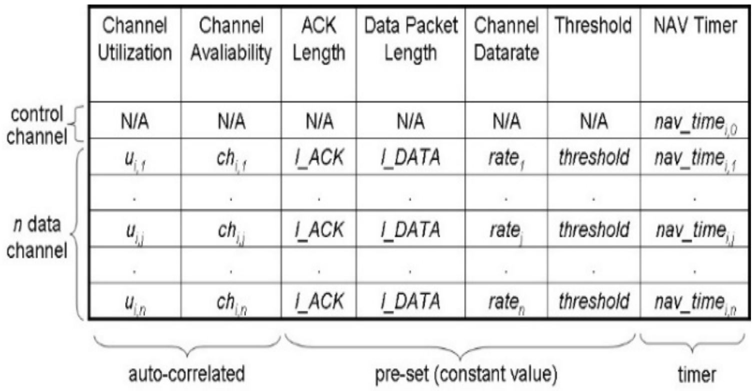


Fig. 4. Channel State Table of SU v_i

The variables $nav\_time_{i,0}$ and $nav\_time_{i,j}$ should be updated in order to protect the performance of the WLAN users. Once $ch_{i,j}$ changes from 0 (idle) to 1 (busy) or v_i has a packet collision with a WLAN user, the channel *j* is likely occupied by a WLAN user, and this WLAN user may transmit another packet over the channel *j* after a SIFS period. In order to avoid the competition of the channel *j* with this WLAN user, v_i sets $nav\_time_{i,j} = \frac{l\_DATA}{rate_j}$, which is larger than a SIFS period. Then, v_i waits at least a SIFS period if v_i tries to use the channel *j* by setting this new value to $nav\_time_{i,j}$.

4 Performance Evaluation

In Section 4.1, the feasibility of using the method in determining *m* by Equation (1) is validated, and the method to set the value of *α* (a predefined weighted factor in Equation (1)) is presented. Accordingly, a suitable value of *α* will be suggested. In Section 4.2, The performance comparison is made between our proposed MAC and the Cognitive MAC proposed in [11] by extensive simulations. For convenience, we use CWC-MAC and POMDP-MAC to denote our proposed MAC and the Cognitive MAC proposed in [11], respectively.

4.1 Continuous-time Markov Chain Models

In this section, two continuous-time Markov chain models for the following two purposes are built in Fig. 5 and Fig. 6. First by using Equation (1), CWC-MAC is efficient in guaranteeing that the performance declination of WLAN users is below than a pre-defined threshold *threshold*. Recall that Equation (1) is used to determine an *m* for transmitting *m* data packets in a RTS-CTS-CRTS-*m*DATA-*m*ACK operation.

Second, since α must be set at first in Equation (1), the effects of different values of α to the performance of CWC-MAC are studied. Accordingly, a suitable value of α will be suggested.

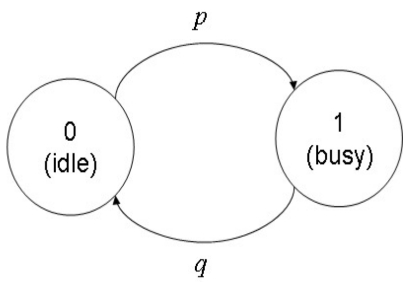


Fig. 5. Markov chains to model a single channel only used by WLAN users

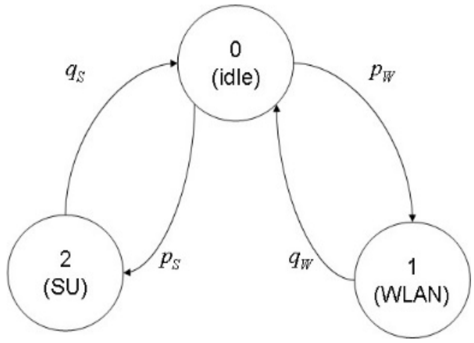


Fig. 6. Markov chains to model a single channel used by WLAN users and SUs

Without loss of generality, we assume that the channels are interference-free from each other, and the channel access behavior of each user is independent with others. In Fig. 5, the first model is used to calculate the performance of a single channel which is only used by WLAN users. Once some SUs execute CWC-MAC to compete for the same channel, the performance impact to the WLAN users is represented in the second model of Fig. 6.

The two modes of Fig. 5 and Fig. 6 are used to derive and compare the performances of the WLAN users in the cases of without and with the SUs, respectively. Based on the derived results, we can deduce the upper bound of the amount of data packets in a RTS-CTS-CRTS-*m*DATA-*m*ACK operation so that the performance declination of WLAN users will be not below than *threshold*. Then, the feasibility of Equation (1) is validated by computing the probability that the determined m in Equation (1) is smaller than the upper bound.

In Fig. 5, there are two states of the channel: state 0 (idle) to state 1 (busy), and each traffic flow generated from the WLAN users arrives and departs with rates p and q, respectively. The channel transits from idle to busy with rate p, and it transits from busy to idle with rate q. We define an infinitesimal generator matrix A to characterize the transition of the states of the Markov chain as follows:

$$A = \begin{bmatrix} -p & p \\ q & -q \end{bmatrix}$$

We have $\Pi A = 0$, where $\Pi = [(1-u), u]$ is the steady-state probability vector, where u denotes the ratio of the channel being busy (i.e., the utilization of the channel), and (1-u) denotes the ratio of this channel being idle. The value of u can be calculated as

$$u = \frac{p}{p+q} \quad \textbf{(2)}$$

where the arrival rate and departure rate of the traffic flows are given by p and q, respectively.

Fig. 6 models a CRN channel, which is jointly competed by SUs and WLAN users. Differently from Fig. 5, there are three states for representing that the channel is idle (i.e., state 0), the channel is occupied by a WLAN user (i.e., state 1), and the channel is occupied by a SU (i.e., state 2), where p_S and q_S denotes the traffic arrival rate and departure rate of traffic flows generated from SUs, respectively. On the other hand, p_W and q_W denotes the two rates of WLAN users. Since WLAN users are reactive PUs, state 2 (channel is used by SU) cannot transits to state 1 (channel is used by WLAN user) directly. The infinitesimal generator matrix A' of the model in Fig. 6 can be written as follows:

$$A = \begin{bmatrix} -(p_w + p_s) & p_w & p_s \\ q_w & -q_w & 0 \\ q_s & 0 & -q_s \end{bmatrix}$$

Similar to the first model, we have $\Pi' A' = 0$, where $\Pi' = [(1 - u_W - u_S), u_W, u_S]$ is the steady-state probability vector, u_W and u_S denote the utilization of the channel by WLAN users and SUs, respectively. By giving p_S, q_S, p_W and q_W, the values of u_S and u_W can be calculated as

$$u_S = \frac{p_s(p_w + q_w) - p_w p_s}{(p_w + q_w)(p_s + q_s) - p_w p_s} \quad \textbf{(3)}$$

$$u_W = \frac{p_w(p_s + q_s) - p_w p_s}{(p_w + q_w)(p_s + q_s) - p_w p_s} \quad \textbf{(4)}$$

When the SUs compete for the same channel with the WLAN users, we attempt to deduce the upper bound by using Equation (4). Since *threshold* is the lower bound ratio of the performance declination of the WLAN users, $u_W = threshold \times u$. Further, $p_W = p$ and $q_W = q$ are set for the reason of having the same traffic arrival rate and departure rate of traffic flows generated from the WLAN users in the cases of without and with the SUs. Then, from Equation (4), q_S can be derived if giving a p_S.

Since q_S is the departure rate of traffic flows generated from the SUs, its reciprocal, i.e., $1/q_S$, equals to the mean value of time period t that the channel is used by the SUs for transmitting packets. Then, t can be used as the upper bound of period for evaluating the feasibility of Equation (1). In other words, the total period (denoted as tp) of transmitting m DATA packets and m ACK packets should be shorter than t. And, $tp = m(t_{\text{DATA}} + t_{\text{ACK}})$, where t_{DATA} and t_{ACK} are the periods of transmitting DATA and ACK, respectively.

For validating the feasibility of Equation (1), we compute the probability (denoted as $P(tp < t)$) that tp is smaller than t by giving a α. The probability $P(tp < t)$ represents the level of guaranteeing the performance of WLAN users. Since the models are stochastic processes with Markov property that the conditional distribution is independent of the past, i.e., t is memory-less and exponentially distributed with its mean value of $1/q_S$, $P(tp < t)$ can be written as

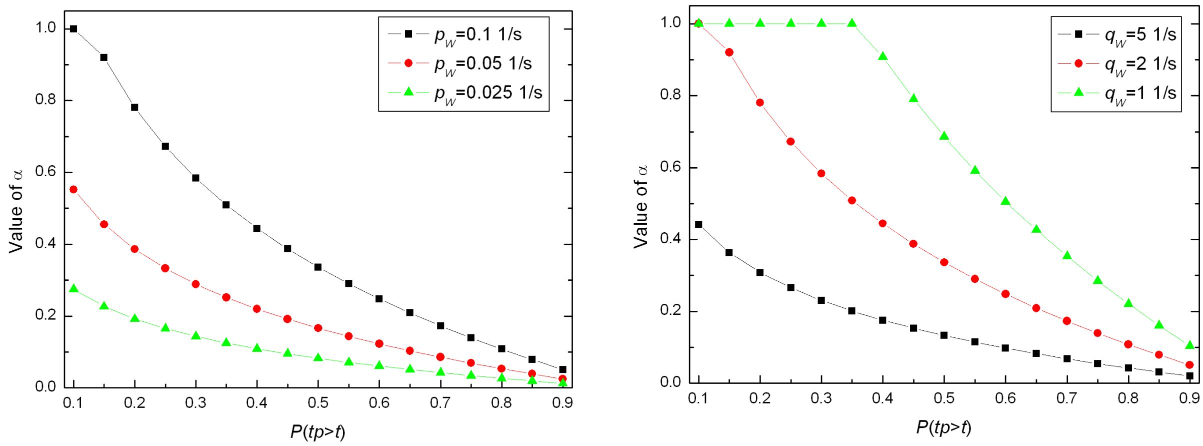
$$P(tp < t) = e^{-q_s tp} \quad \textbf{(5)}$$

From $tp = m(t_{\text{DATA}} + t_{\text{ACK}})$ and $m = \left\lfloor a \times \left\lfloor k \times (1 - \frac{l\_ACK}{l\_DATA}) \right\rfloor \right\rfloor$ (i.e., Equation (1)), the relation of α and $P(tp < t)$ can be analyzed. The results are demonstrated in Fig. 7, which can be used for suggesting a suitable value of α based on the required level of guaranteeing the performance of WLAN users. Table 2 summarizes the parameters and their assigned values for the analysis.

Table 2. Analysis parameters

Parameters	Values
$t_{\text{DATA}} + t_{\text{ACK}}$	1 ms
p_W	{0.1 1/s, 0.05 1/s, 0.025 1/s}
q_W	{5 1/s, 2 1/s, 1 1/s}
p_S	0.1 1/s
threshold	0.9

In Fig. 7, the relations are evaluated for varying p_W and q_W. For simplify, $t_{\text{DATA}} + t_{\text{ACK}} = 1$ ms, $p_S = 0.05$ 1/s, and *threshold* = 0.9. In Fig. 7(a), q_W is set to a fixed value of 2, and the three lines represent the relations based on the three different values of p_W. In Fig. 7(b), p_W is set to a fixed value of 0.1, and the three lines represent the relations based on the three different values of q_W.



(a) $q_W = 2$ 1/s (b) $p_W = 0.1$ 1/s

Fig. 7. Relation of the values of α and $P(tp < t)$

Two results can be derived from Fig. 7. First, α should be decreased with increasing $P(tp < t)$. That is a smaller α should be given when the required level of guaranteeing the performance of WLAN users is high, since a smaller α will induce a smaller m. Then, SUs can protect the performance of WLAN users by occupying the channel for a shorter period (i.e., smaller tp), which is derived by the smaller m.

Second, α is increased with increasing p_W in the cases with the same $P(tp < t)$. That is we can set a larger α, if the WLAN users have higher traffic arrival rate but their $P(tp < t)$ is not changed. When higher traffic arrival rate is generated from the WLAN users, i.e., higher $u_{i,j}$, a smaller k is derived by the equation $(1-u_{i,j})^k > threshold$ (which is mentioned in Section 3.2). Recall that tp is determined by m while m is determined by α and k. Since α is derived from Equation (5) by giving the same $P(tp < t)$, we can obtain a larger α not only for obtaining a larger tp for increasing the performance of SUs, but also protecting the performance of the WLAN users with the same level.

4.2 Simulation Results

Simulations are implemented using the Network Simulator 2 package [21]. There are two kinds of users, i.e., WLAN users and SUs. The WLAN users use IEEE 802.11 distribution coordination function (DCF) as the MAC protocol, and the SUs use the two proposed MAC protocols, i.e., CWC-MAC and POMDP-MAC, for comparing the performance of the two proposed protocols. The packets are sent using the un-slotted CSMA/CA. One control channel and five data channels are available for the users. Fifty runs with different seed numbers are conducted for each scenario and collected data for these runs are averaged.

In the simulations, five sender-receiver pairs of WLAN users occupy the five data channels, and five sender-receiver pairs of SUs attempt to access the above five data channels. Each of these SUs is equipped with two transceivers whose transmission range is up to 250 meters. One of SU's transceiver access the control channel and the other transceiver accesses the data channels. The WLAN senders send burst traffic flows by an ON-OFF traffic generator, where busy periods and idle periods are exponentially distributed with different mean values. The SU senders attempt to transmit saturated CBR traffic flows for improving the utilization of the five data channels. Each user has a MAC layer FIFO transmission queue of 50 packets at maximum. The data channel rate and *threshold* of the all data channels is 11 Mbps and 0.99, respectively. The value of α is set to 0.7. Table 3 summarizes the parameters and their assigned values for the simulations.

Table 3. Simulation environment

Parameter	Value
α	0.7
threshold	0.99
SIFS period	10 us
DIFS period	50 us
RTS length	20/28~60 bytes*1
CTS length	14/20 bytes*2
CRTS length	20 bytes
ACK length	14 bytes
Data packet length	1000 bytes

*1: In CWC-MAC, RTS length is 28~60 bytes. In both POMDP-MAC and 802.11, RTS length is 20 bytes.
*2: In CWC-MAC and POMDP-MAC, CTS length is 20 bytes. In 802.11, CTS length is 14 bytes.

There are three performance measures: number of received DATA bytes per second, decline rate, and overhead rate. The number of received DATA bytes per second is averaged from the numbers of received DATA bytes by the channels in a second, and it can reflect the throughput of the channels. The decline rate is defined as the ratio of number of received DATA bytes of WLAN users in the case of with the competition to that in the case of without the competition, it can reflect the performance declination of WLAN users when some SUs compete for the same channels with these WLAN users. The overhead rate is defined as the ratio of the number of bytes for transmitting the control packets to that for transmitting all packets (including control and data packets). Further, we validate the effectiveness of CWC-MAC in protecting the performance of WLAN users by checking whether the decline rate is above *threshold*.

In Fig. 8, we use the ON-OFF traffic generator to generate the WLAN traffic flows by setting the WLAN traffic rate varied from 10% to 40%. The WLAN traffic rate is defined as the mean value of busy periods to that of whole periods (including busy and idle periods). For example, if the mean busy and idle period is 1 second and 4 seconds, respectively, the rate is 20% which is derived from 1/(1 + 4). In Fig. 8, the varied rates are set to compare the performance of POMDP-MAC with CWC-MAC.

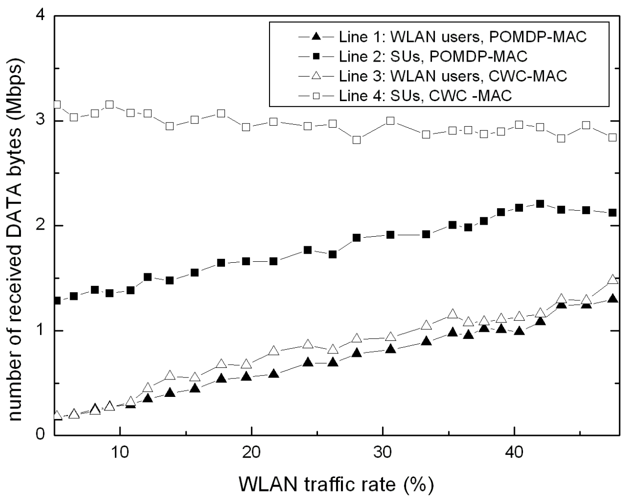


Fig. 8. Number of received DATA bytes

The simulation results of Fig. 8 are showed by four lines. The line 1 and the line 2 represent the numbers of DATA bytes received by the WLAN users and by the SUs when POMDP-MAC is used by the WLAN users and the SUs, respectively. On the other hand, Line 3 and line 4 represent the numbers when CWC-MAC is used. As observed from line 1 and line 3, the WLAN users receive fewer DATA bytes as a consequence that CWC-MAC avoids the improper channel allocation by using the proposed RTS-CTS-CRTS handshake. It reveals that when using CWC-MAC, the interference to WLAN users is smaller than that of using POMDP-MAC. The line 2 and the line 4 show that using active traffic control mechanism of CWC-MAC makes the SUs to receive much more DATA bytes than using POMDP-MAC. CWC-MAC is effective in using unused spectrum resources.

Fig. 9 further validates the effectiveness of CWC-MAC in avoiding interference to the WLAN users. It shows that the average decline rate (= 0.992) of CWC-MAC is larger than *threshold* (= 0.99), whereas the average decline rate (= 0.915) of POMDP-MAC is smaller than *threshold* (= 0.99). The results reveal that CWC-MAC is more effective in protecting the performance of WLAN users than POMDP-MAC.

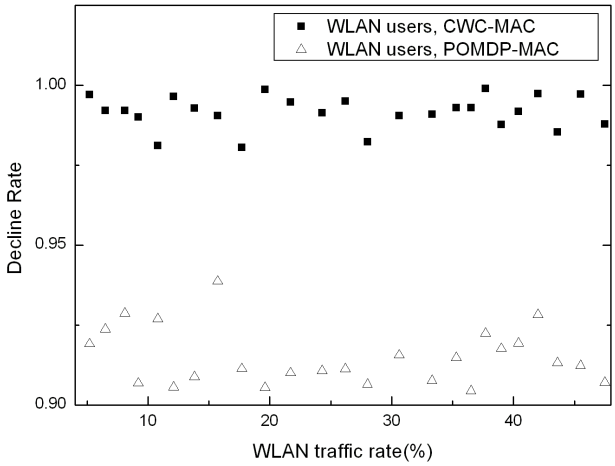


Fig. 9. Decline rates

In Fig. 10, the bars labelled RTS, CTS and CRTS represent the overhead rates of RTS, CTS and CRTS packet bytes, respectively. For example, the overhead rate of RTS is the ratio of the number of bytes for transmitting the control packets to that for transmitting all packets. The bar labelled TOTAL represents the overhead rates of all control packet (including RTS, CTS and CRTS packets) bytes. Fig. 10 shows that CWC-MAC induces no more or even fewer control bytes than POMDP-MAC, although CWC-MAC make both of WLAN users and SUs with more received DATA bytes as shown in Fig. 8. It reveals that CWC-MAC has smaller overhead rate than POMDP-MAC.

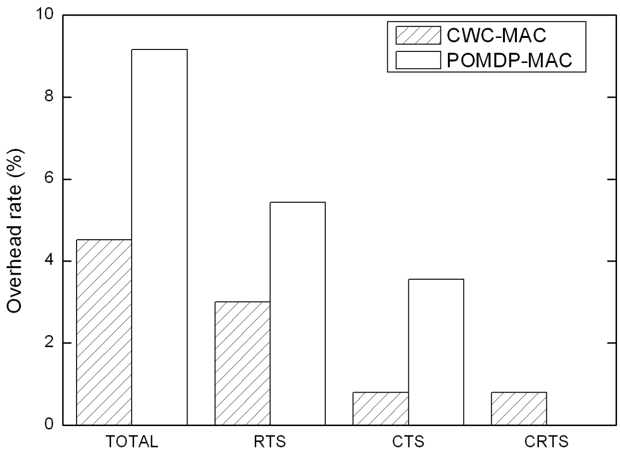


Fig. 10. Overhead rates

5 Conclusion

In order to improve the unused spectrum utilization and protect the performance of WLAN users, a CRN MAC, named CWC-MAC, has been proposed. In CWC-MAC, two mechanisms, RTS-CTS-CRTS handshake mechanism and active traffic control mechanism, are proposed for solving the problem of improper channel allocation and allowing SUs to use the unused spectrum. The RTS-CTS-CRTS handshake mechanism can select a channel with better transmission quality. Then, the active traffic control mechanism is used to control the amount of DATA packets transmitted on the selected channel. By the aid of the two mechanisms, the performance declination of the WLAN users can be guaranteed below a pre-defined threshold.

The mathematical analytical results based on Markov chain models validate the performance guarantee. Performance comparison is made between CWC-MAC and POMDP-MAC. The simulation results show that CWC-MAC is superior to POMDP-MAC in avoiding interference to the WLAN users, using unused spectrum resources, and inducing less overhead.

One thing needs to be mentioned here. A drawback of CWC-MAC is to set a fixed packet size of DATA. As part of our future works, we expect CWC-MAC to provide better performance by dynamically adjusting the size. We will study the effects of factors on the selection of the packet sizes of DATA, estimate the numerical influences of these factors on the selection, and then refine CWC-MAC accordingly.

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