A Cognitive MAC Protocol for QoS Provisioning in Overlaying Ad Hoc Networks [1]

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***Abstract*— Cognitive Radio (CR) can effectively reuse the same frequency of the existing legacy systems with the help of the adaptivity provided by the software defined radio technique and the intelligence learned by sensing the huge spectrum in the surrounding environment. One fundamental issue for a CR network is how CR users establish an overlaying ad hoc link on licensed and unlicensed bands. On licensed band, the CR user has to detect the presence of the primary user and vacate accordingly to avoid the interference. On the unlicensed band, the medium access shall support the quality of service (QoS) as well as improving the efficiency and fairness for the spectrum usage. In this paper, by moderately reshaping the legacy carrier sense multiple access (CSMA) medium access control (MAC) protocol, we propose a cognitive and distributive MAC protocol to establish a CR ad hoc network with QoS provisioning, high efficiency and fairness. Through the simulations by NS-2, the proposed cognitive MAC protocol can improve throughput by 50% compared to the legacy carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol, while keeping the dropping rate less than 2% for delay-sensitive applications.**

I. INTRODUCTION

As the advances of wireless technologies, various wireless systems with fixed and non-overlapped frequency spectrum simultaneously exist in our daily lives. However, the fixed spectrum allocation may not be always effectively used everywhere. The cognitive radio (CR) is proposed to reuse the spectrum of the existing legacy system on licensed and unlicensed frequency bands to establish unharmful and temporary connections [1]–[5]. Some key features for the CR network include

- radio sensing to huge spectrum [6]–[8];
- spectrum identification in terms of location and time [9]–[11];
- opportunity allocation in terms of frequency band [12]–[14].

On licensed and unlicensed bands, the objectives of CR networks are slightly different [15]. On licensed band, the CR functions aim to detect the presence of primary users and vacate the occupied spectrum to avoid the interference. On the other hand, the CR functions on unlicensed band have to improvethe efficiency and fairness of spectrum usage as well as support the quality of service (QoS). Thus, referring to

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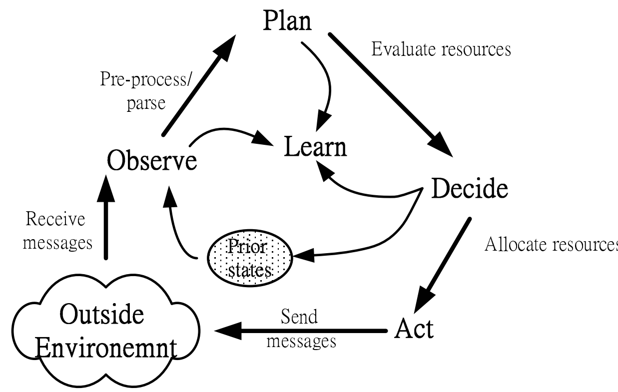


Fig. 1. The cognition cycle [16].

Fig. 1 and according to [5], [16], the main functionality of a cognitive MAC protocol can be summarized as follows:

- ***observe*** stage - to sense the surrounding environment and record the spectrum usage of the existing legacy systems;
- ***plan*** stage - to evaluate if a temporary ad hoc link can be established without interfering current users;
- ***decide*** stage - to determine the transmitted power, frequency, duration and schedule the frame transmissions;
- ***act*** stage - to perform transmission with specified resources at the scheduled time.

In the literature, most of studies for MAC protocol design focus on the dynamic spectrum selection [12]–[14]. While accessing the selected spectrum, the CR user requires to accordingly adjust its MAC functions [17]. However, a generic cognitive MAC protocol for the spectrum access with emphasis on achieving the objectives of CR networks has rarely been seen in the literature.

The main contribution of this paper is to propose such an efficient and fair MAC protocol as well as QoS provisioning for a CR device while coexisting with the legacy users on both licensed and unlicensed bands. The proposed cognitive MAC protocol is based on the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. Different from the legacy CSMA/CA, the propose MAC protocol introduces several mechanisms and algorithms to satisfy the objectives of the CR network on licensed and unlicensed bands. Specifically, in the ***observe*** stage, we propose a neighbor list establishment to help a station recognize the spectrum opportunities. In the ***plan*** stage, an improved contention resolution mechanism, consisting of the gating mechanism, linear backoff algorithm and stall avoidance scheme, is suggested to enhance the overall performance of throughput, access delay and fairness. In the ***decide*** stage, a novel invited reservation procedure is developed to ensure a CR user satisfying QoS requirements. At last, in the ***act*** stage, a distributed frame synchronization mechanism is proposed to coordinate frame transmissions without a centralized controller.

II. Neighbor List Establishment in *Observe* Stage

To have the knowledge of the spectrum usage, we suggest a neighbor list establishment to record the information of the primary and CR users in the ***observe*** stage of the cognition cycle. In this mechanism, we partition the observed frames into three categories and store the observed information into three tables: Primary user information table (PIT), Reservation Information Table (RIT) and Contention Information Table (CIT).

- Primary user Information Table (PIT) stores the information of primary users in the existing legacy system including: 1) the existing legacy system of the primary user; 2) the address of the primary user; 3) the duration of the primary user's transmissions. It records the spectrum usage time of the primary user to avoid interfering the existing legacy system.
- Reservation Information Table (RIT) saves the reservation information of delay-sensitive traffic flows including: 1) the source address of the delay-sensitive traffic flow; 2) the length of the subsequent frame in the delay-sensitive traffic flow; 3) the sequence number of the delay-sensitive traffic flow. It collects the length of the subsequent delay-sensitive frame in the MAC header of the delay-sensitive data and its ACK frames. In addition, the sequence in RIT maps the delay-sensitive traffic frame transmissions. Therefore, with the frame length and transmission sequence of delay-sensitive traffic flows, all the stations can be aware of the reserved time and thus avoid collisions.
- Contention Information Table (CIT) records the properties of non-real-time traffic including: 1) the source address of the non-real-time data traffic flow; 2) the transmission time of the observed frame; 3) the number of non-real-time data traffic flows. It provides the number of non-real-time traffic flows, which can be used to reduce the collisions and improve the channel throughput in the ***act*** stage of the cognition cycle.

To correctly establish PIT, RIT and CIT, a CR user is designed to observe the status of frame transmissions around its neighborhood for a period of T_{obv}. The duration of T_{obv} must be longer than the maximum repetition period between two successive delay-sensitive frame. To ease notations, we hereafter denote *rt-nodes* and *nrt-nodes* as the CR users sending delay-sensitive and non-real-time frames, respectively.

III. Contention Resolution in *Plan* Stage

In the ***plan*** stage of the cognition cycle, the cognitive MAC protocol has three functions. One is to prevent the CR users from interfering the existing legacy system, and the other is to efficiently and fairly access the unused spectrum during a short spare time. To this end, we suggest three improved approaches as follows:

1) gating mechanism - to forbid the transmissions that may interfere the primary users or collide other CR users;
2) linear backoff algorithm - to expedite the channel access for delay-sensitive traffic;
3) stall avoidance scheme - to improve the fairness of frame access among *nrt-nodes*.

A. Gating Mechanism

The gating mechanism is used to avoid interfering the primary users of the existing legacy system and to reduce the collisions among the CR users. The basic idea is cooperating the spectrum sensing and identification techniques to prevent from interfering the primary users. In addition, a modified *p*-persistent CSMA algorithm is used to reduce the collisions among CR users during a short spare time, where the optimal value of *p* can be computed according to the number of *nrt-nodes* [18]. The calculation for the optimal value of *p* will be shown in our journal version due to page limit. The detailed procedures of the proposed gating mechanism are described as follows:

1) When a CR user is requested for transmission, the gating mechanism first checks whether a legacy user occupies the channel or not.
   - If so, the transmission of this CR user is deferred.
   - Otherwise, the optimal transmission probability *p* is calculated.
2) Apply the *p*-persistent algorithm to determine whether the frame can be transmitted or not:
   - If the frame is granted for transmission, the CR user immediately sends the frame.
   - Otherwise, the frame will be deferred and again contend for the channel access.

B. Linear Backoff Algorithm

To expedite the channel access for delay-sensitive flows, we suggest that the request of this kind of traffic flows shall follow the linear backoff algorithm instead of increasing the CW size exponentially as in the legacy CSMA/CA MAC protocol. That is, if the request of the delay-sensitive traffic flow is collided, the CW size (CW_{rt}) increases according to the following principle:

$$CW_{rt} = \min(CW_{max}, CW_{min} \times (N\_att - 1)), \qquad (1)$$

where N_att is the number of attempts for sending the request; CW_{max} and CW_{min} are the maximum and the minimum CW sizes, respectively. From (1), the channel access of a delay-sensitive traffic flow can be faster than that of the non-real-time data flows.

As long as the request of a delay-sensitive traffic flow is successfully transmitted, the remained frames are sent in the reserved time slot according to the proposed invited reservation procedure (which will be discussed in Section IV). Because only the request contends for accessing the channel, the number of attempts for establishing delay-sensitive traffic flows is much fewer than that of non-real-time data frame based on our design. Thus, the proposed MAC protocol can avoid the high collisions issue of the linear backoff algorithm, while reducing the access delay for the request of the delay-sensitive traffic flow.

C. Stall Avoidance Scheme

To improve the fairness for the access in short spare time, we develop a stall avoidance scheme aiming to reduce the transmission delay of the *nrt-nodes* with excessive buffered frames. The specific goal is to minimize the variance of the transmission delay, including the waiting time in the queue and the channel access time, among all the *nrt-nodes*. Obviously, the variance of transmission delay reduces as soon as the back-logged frames can be transmitted early.

The suggested stall avoidance scheme with respect to the *nrt-nodes* is described as follows. Select a pre-determined threshold value for the maximum allowable buffered data frames ($\mathrm{Q}_{\mathrm{threshold}}$) and the guaranteed CW size for the stalled *nrt-nodes* CW_{stall}, where

$$CW_{stall} < CW_{min}. \tag{2}$$

If the buffered frames in an *nrt-node* is more than $\mathrm{Q}_{\mathrm{threshold}}$, the CW size of the subsequent frames in the queue is reduced to CW_{stall}. Because a smaller CW size leads to a higher transmission probability, the lagging frames in a stalled *nrt-node* with CW_{stall} can be transmitted earlier, thereby improving the fairness among the *nrt-nodes*.

IV. Invited Reservation Procedure in *Decide* Stage

Since any connection in a CR network cannot interfere the existing legacy system, the key challenge in designing the cognitive MAC protocol lies in the way of support the QoS for delay-sensitive traffic flows. To solve this problem, we propose an invited reservation procedure in the ***decide*** stage of the cognition cycle.

A. Invited Reservation Procedure

The invited reservation procedure is designed for supporting the delay-sensitive flows. Based on this procedure, the receiver is responsible for sending the real-time clear-to-send (rt-CTS) control frame to invite the frame transmission as well as reserving the time slot for subsequent delay-sensitive frames. In this way, the rt-CTS frame can be used to forbid other users' transmissions. The collisions due to the hidden node problem are also somehow alleviated. In addition, since the CR receiver also learns the spectrum usage time of the primary users in ***observe*** stage, the invited reservation procedure is capable of dynamically adjusting the invitation without interfering the primary users.

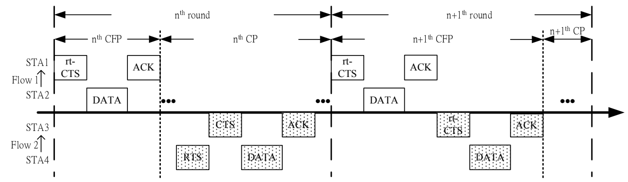


Fig. 2. The timing diagram for the invited reservation procedure.

B. Link Establishment with Invited Reservation Procedure

Figure 2 illustrates how a delay-sensitive traffic flow is established based on the invited reservation procedure. In Flow 2 (STA 4 → STA 3), STA 4 follows the request-to-send/clear-to-send (RTS/CTS) handshaking procedure to send the request of a delay-sensitive flow in the $\mathrm{n^{th}}$ contention period (CP). As long as the flow is established, STA 3 sends rt-CTS to inform STA 4 with reserved information for the rest of frames. Accordingly, without contention, STA 4 transmits the rest of frames in the $\mathrm{(n+1)^{th}}$ and successive contention free period (CFP).

As shown in Fig. 2, the total transmission time in each round is partitioned into two periods: the CFP and CP. Obviously, the longer the CFP the shorter the CP. Thus, one important induced issue is to appropriately allocate the time duration of the two periods so that the delay constraints for the delay-sensitive traffic flow can be satisfied, while its impact on the non-real-time transmissions can be limited to an acceptable level. This issue can be resolved by the aforementioned stall avoidance scheme. Recall that the stall avoidance scheme reduces the CW size of the stalled *nrt-node* to CW_{stall}, which is smaller than CW_{min}. Because the request of a delay-sensitive traffic flow still contends for the channel access with CW_{min}, the stalled non-real-time frame with CW_{stall} can have a higher probability to win the channel contention. Thus, the delay of non-real-time frames can be still controlled within a reasonable range based on our proposed cognitive MAC protocol and retain a certain level of fairness between different priority traffic flows.

V. Distributed Frame Synchronization Mechanism in *Act* Stage

Another important issue in the ***act*** stage is to develop a distributed approach to ensure the frame synchronization among all the CR users. The objective of frame synchronization is to inform the stations the starting time of the CFP and CP.

The basic idea of the proposed distributed synchronization algorithm is to use the rt-CTS and ACK control frames of the first and last delay-sensitive traffic flows to indicate the starts of the CFP and the CP, respectively. Since a CR user establishes its neighbor list in the ***observe*** stage, the information in the RIT can be used to identify the first and last *rt-nodes*. Thus, when sensing the channel is available, the first receiver in the RIT broadcasts rt-CTS frame to start a new CFP. During the CFP, the *rt-nodes* transmit frames based on the sequence in the RIT, whereas the *nrt-nodes* wait until receiving the ACK frame from the last receiver in RIT. Therefore, all

TABLE I

SIMULATION PARAMETER.

Cover Range	10m×10m
Data Rate	2 Mbps
Simulation time	100 sec
Unit slot time	20 μsec
SIFS/PIFS/DIFS	10/30/50 μsec
Repetition period of delay-sensitive traffic	20.48 msec
Min. and Max. CW size	31/1023
CW for stall avoidance (CW_{stall})	15

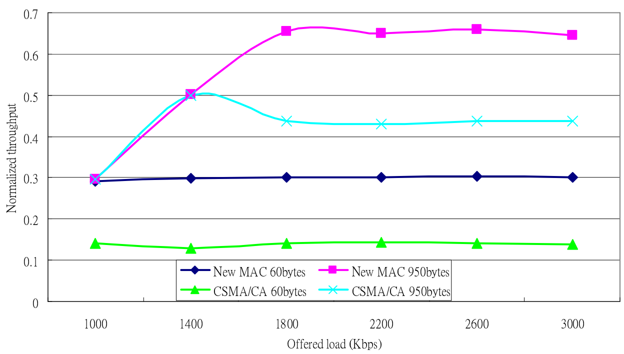


Fig. 3. Throughput comparison of the proposed cognitive MAC protocol with the traditional CSMA/CA MAC protocol.

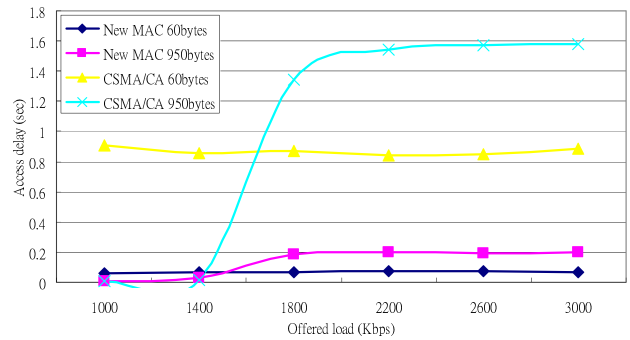
the stations can access the channel in the designated period without influencing the transmissions in the reserved time.

VI. SIMULATION

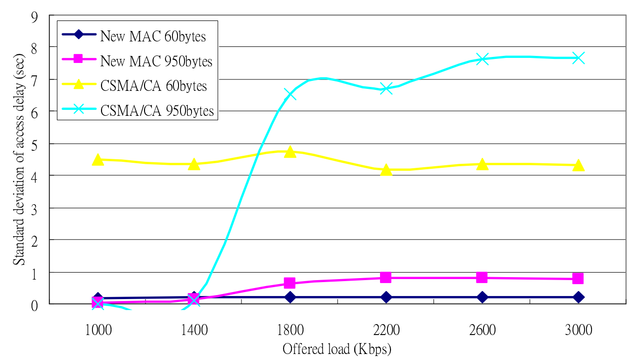
In this section, we demonstrate the performance of the proposed cognitive MAC protocol through the NS-2 simulator [19]. In the following simulations, 40 *nrt-nodes* establish non-real-time data flows modeled by the Poisson process in the presence of 5 *rt-nodes* and primary users transmitting voice traffic using the proposed MAC protocol and traditional time division multiple access (TDMA). The voice traffic is modelled by an interrupted Poisson process, i.e. one 164-byte frame is generated every 20.48 msec in the “On” state but no frame is generated in the “Off” state. The duration of the “On” and “Off” states follows the exponential distribution with the average duration of 1 and 1.3 seconds, respectively. All the nodes locate within the cover range as shown in Table I and can hear with each other all the time. The related simulation parameters are listed in Table I.

A. Numerical Results

Figure 3 compares the normalized throughput of the proposed MAC protocol with that of the legacy CSMA/CA MAC protocol. For the frame sizes of 60 and 950 bytes, the throughput of the proposed MAC protocol are 100% and 50% better than those of the CSMA/CA MAC protocol, respectively. The improvements mainly result from the invited reservation procedure, which can control the delay for the delay-sensitive frames. Thus, all the received delay-sensitive frames can be counted for throughput. Furthermore, the gating mechanism in the proposed cognitive MAC protocol reduces the collisions in the CP. On the contrary, all the frames based



(a)



(b)

Fig. 4. Comparison of the proposed cognitive MAC protocol and CSMA/CA MAC protocol in terms of (a) mean access delay and (b) fairness.

on the legacy CSMA/CA MAC protocol have to contend for the channel. Therefore, lots of delay-sensitive frames are unable to meet the delay constraint due to retransmissions and decreasing the throughput performance.

Figures 4(a) and (b) compare the mean access delay and fairness performance between the two MAC protocols. For the proposed MAC protocol, the mean access delay and its maximum standard deviation in sending the Telnet data frames is less than 0.2 sec and 1 sec, respectively. However, for the legacy CSMA/CA MAC protocol, the mean access delay and its maximum standard deviation are increased by about 6 times to 1.5 sec and 6 sec, respectively. The long access delay and its maximum standard deviation in the CSMA/CA MAC protocol is due to the long waiting time in the queue. However, when the non-real-time frames are back-logged, the proposed stall avoidance scheme can effectively reduce the CW size of the stalled frames to expedite the transmissions. Therefore, the proposed MAC protocol can reduce the waiting time and improve the fairness performance.

Figure 5 compares the two considered MAC protocols in terms of dropping rate. As shown in the figure, the dropping rate of the proposed MAC protocol is lower than 0.1%, while the dropping rate in the legacy CSMA/CA MAC protocol can

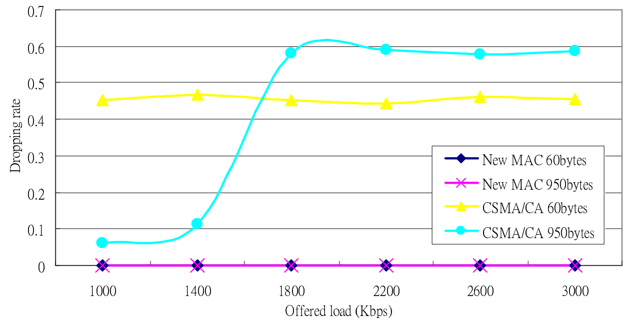


Fig. 5. Dropping rate of voice traffic flows.

be higher than 40% under the condition of heavy traffic load. Because voice frames need to contend for the channel with the same priority with data frames based on the legacy CSMA/CA MAC protocol, the retransmissions due to the collisions may cause long access delay beyond the delay constraint. By contrast, with the help of the invited reservation procedure, the proposed MAC protocol can guarantee the delay-sensitive frames to be received within the predefined constraint of 40 msec. Therefore, the dropping rate of the proposed MAC protocol is almost negligible compared to the CSMA/CA MAC protocol.

VII. CONCLUSION

In this paper, we have proposed a cognitive MAC protocol to establish a CR ad hoc network with QoS provisioning in the presence of the legacy wireless systems. The proposed mechanisms can supplement the insufficiency of the legacy CSMA/CA MAC protocol to fulfill the goals of the cognitive wireless networks. With respect to the four stages of the cognition cycle, we suggest the following techniques:

- **Neighbor list establishment** in the ***observe*** stage: to help a CR user have the knowledge of the spectrum usage of the primary users and CR users;
- **Improved contention resolution algorithm** in the ***plan*** stage: to prevent CR users from interfering the existing legacy system and to allow CR users to effectively and efficiently access the channel in the spare time of the primary users.
- **Invited reservation procedure** in the ***decide*** stage: to schedule the transmissions of delay-sensitive traffic with satisfactory QoS requirements without interfering the primary users and to dynamically allocate the bandwidth for various traffic types to avoid the starvation issue for low priority traffic.
- **Distributed frame synchronization** in the ***act*** stage: to distributively coordinate the frame transmissions among the CR users.

Through the simulations by NS-2, we demonstrate that in the hidden node environment, the throughput performance of the proposed MAC protocol is at least 50% better than that of the legacy CSMA/CA MAC protocol. The mean access delay and its maximum standard deviation of the proposed MAC protocol are 6 times less than the CSMA/CA MAC protocol. At last, instead of more than 40 % for the legacy CSMA/CA MAC protocol, the dropping rate of delay-sensitive traffic for the proposed MAC protocol is almost negligible.

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