Multiple Access Control with Adaptive Spectrum Sensing Technique for Cognitive Radio Networks

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Abstract—**Cognitive Radio (CR) is a promising technology to resolve the spectrum scarcity issue of future wireless networks. In CR networks, Secondary Users (SUs) opportunistically access the temporal and spatial white spaces of the spectrum band licensed for Primary Users (PUs). In principle, SUs are required to vacate the licensed channel as soon as adjacent PUs are active. However, the imperfect spectrum sensing capability of SUs makes the ongoing communication of PUs vulnerable. We can decrease the sensing error probability by increasing the spectrum sensing time, but it sacrifices the system throughput significantly. In this paper, we propose a Multiple Access Control (MAC) algorithm with the adaptive spectrum sensing time, where the SUs choose the spectrum sensing time depending on the previous activity of PUs and the packet transmission result, to compromise the balance between the sensing time and the system throughput. Furthermore, our scheme definitely protects the ongoing transmissions of PUs and other SUs through the sequential spectrum sensing in both the secondary transmitter and the secondary receiver. Numerical results show that the proposed algorithm outperforms the standard CSMA/CA with the long spectrum sensing time.**

Keywords-cognitive radio; spectrum sensing; carrier sensing; multiple access control; CSMA/CA

I. INTRODUCTION

Spectrum efficiency has almost reached the theoretical upper bound, i.e. Shannon capacity [1]. However, the widespread mobile devices still require the huge wireless spectrum. The situation becomes worse since even the Industrial Scientific and Medical (ISM) band is expected to be saturated in the near future. Moreover, the current static spectrum allocation policy hinders the efficient utilization of spectrum resources. Fortunately, according to various observations [2][3], there are many licensed spectrum bands underutilized or unutilized at all. The Cognitive Radio (CR) technology, which enables the Dynamic Spectrum Access (DSA), is now attracting much attention as a potential solution to the spectrum scarcity problem [4].

The CR networks consist of a primary network and multiple secondary networks. Usually they operate in a non-cooperative manner without mutual communications. The unlicensed Secondary Users (SUs) occupy the unused spectrum of the licensed primary network opportunistically. Hence, SUs are required to vacate the occupying channel within a predetermined time, whenever it is claimed by Primary Users (PUs).

We can classify the architecture of CR networks into the centralized network and the decentralized network. Among these, the decentralized network, called CR Ad-Hoc Network (CRAHN), has many advantages such as easy implementation, less cost, no need for infrastructure etc. However, in the CRAHN, it is hard to guarantee the channel access priority of PUs due to its intrinsic features such as dynamic network topology, self-organization, and lack of the centralized control. To protect the licensed PUs, the SUs are mandated to equip the functionality of detecting the communication activity on the channel. Therefore, the performance of CR networks heavily depends upon the spectrum sensing capability of SUs. Intuitively, long sensing time is desirable for the reliable spectrum sensing results. However, it wastes the potential transmission time and reduces the system throughput. Short sensing time can be beneficial for the throughput of the secondary networks, but it can disturb the ongoing communication of PUs frequently.

In this paper, we design a Multiple Access Control (MAC) protocol for CR networks, which judiciously controls the sensing time depending on the previous activity of PUs as well as the packet transmission result. Our scheme attains the good balance between the spectrum sensing time and the throughput of SUs. To this end, we use the Spectrum Sensing (SS) and the Carrier Sensing (CS) at the same time. Furthermore, we adopt two types of SS, i.e. fine sensing and fast sensing, and choose the best sensing type in the given situation. Our proposed protocol extends the standard CSMA/CA such that for the data transmission, SUs follow the procedure: SS by the transmitter, NTS (Notify-To-Send), SS by the receiver, RTS, CTS, DATA and ACK in sequence. The SS in both transmitter and receiver protects the PUs from the secondary transmitter and at the same time, the secondary receiver from the hidden PU also.

The rest of this paper is organized as follows. In Section II, we describe the system model. In Section III, we propose a MAC protocol with the adaptive spectrum sensing algorithm. We evaluate the performance of our proposed scheme in Section IV by the numerical analysis, and make a conclusion in Section V.

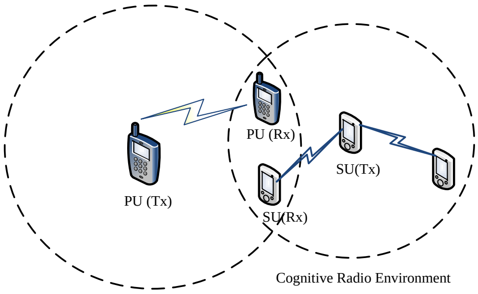

Figure 1. Considered system.

II. SYSTEM MODEL

We consider a secondary network collocated with a primary network, as shown in Fig. 1. We assume that both networks do not share any control information each other, i.e. they operate non-cooperatively. The SUs can carry out data transmission over the licensed spectrum channel of the primary network through DSA. However, they are bound to vacate the channel when it is claimed by the PUs. We assume that the channel is error-free such that packets are lost only due to the collision among SUs or interference from PUs. Without loss of generality, we assume that the system time is divided into time slots of the equal interval σ.

We denote the secondary transmitter under consideration as $\mathbb{S}_t$ and the corresponding secondary receiver as $\mathbb{S}_r$, respectively. Let $\mathbb{p}_t$ denote the primary user(s) that can be interfered by the transmission of $\mathbb{S}_t$. Similarly, $\mathbb{p}_r$ denotes the primary user(s) affected by the transmission of $\mathbb{S}_r$. In such a setup, the channel is available to the secondary network only when the neighboring PUs of $\mathbb{S}_t$ and $\mathbb{S}_r$ (i.e. $\mathbb{p}_t$ and $\mathbb{p}_r$) are inactive all. When an SU performs a channel sensing, the channel can be detected as 'active' or 'inactive'. The event H_1 indicates that the channel is detected as 'active', and H_0 indicates that the channel is detected as 'inactive'. The energy detector does not produce the correct result always such that there is the possibility of false alarms and misdetections.

III. PROPOSED MAC PROTOCOL

A. Operation of Proposed Scheme

Our proposed MAC protocol extends the traditional RTS/CTS mechanism of IEEE 802.11 WLAN to the NTS/RTS/CTS. The new control packet, NTS, contains the information such as receiver address, packet type and spectrum sensing time (or spectrum sensing type). The successful sharing of NTS within a secondary network allows the secondary transmitter $\mathbb{S}_t$ to be synchronized with the corresponding $\mathbb{S}_r$ to sense the channel status.

We illustrate the operation of the transmitter $\mathbb{S}_t$ in Fig. 2 by the flow chart. Each SU, who desires to transmit a data packet, initializes the backoff counter to a random number within the contention window. If the channel is idle for the DIFS interval, the SU decides the channel to be clear, and decreases the backoff counter one by one every idle time slot. If the backoff counter reaches zero, the SU carries out SS. The SU chooses the type of spectrum sensing among the fast sensing and the

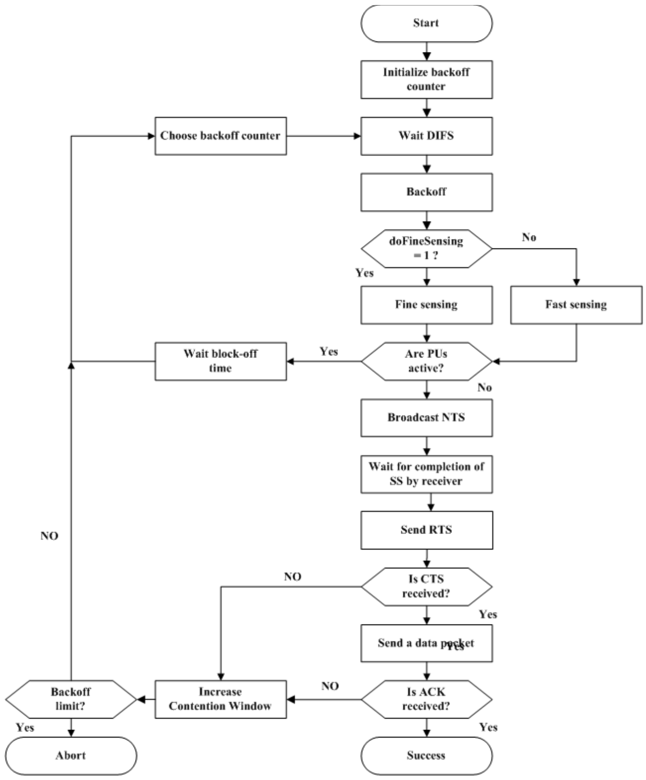

Figure 2. Operation of the secondary transmitter.

fine sensing, through the PU Activity Oriented Sensing Type (POST) algorithm explained soon. If the SU, $\mathbb{S}_t$, detects that $\mathbb{p}_t$ is active, it enters into the blocking state and defers the transmission for a blocking period, set in advance. Otherwise, the $\mathbb{S}_t$ broadcasts the NTS packet to notify the adjacent SUs that the upcoming period is reserved for the SS of the designated receiver, $\mathbb{S}_r$. In the sequel, $\mathbb{S}_r$ performs the SS according to the type of spectrum sensing specified in the NTS. If the $\mathbb{S}_r$ finds that $\mathbb{p}_r$ is active, it enters into the blocking state to avoid the interference to the PU, and freezes its backoff counter until the expiry of its blocking period. If the blocking period completes, the secondary receiver decreases its backoff counter every idle time slot. The spectrum sensing conducted by $\mathbb{S}_t$ and $\mathbb{S}_r$ both ensures that the SUs do not transmit packets while the primary users are active.

After broadcasting NTS, $\mathbb{S}_t$ waits for a fixed time for the $\mathbb{S}_r$ to execute the SS without intervention. It then tries to exchange RTS and CTS with the receiver to continue the data transmission procedure. If $\mathbb{S}_t$ does not receive CTS from $\mathbb{S}_r$ until the RTS plus SIFS time, $\mathbb{S}_t$ concludes that the RTS has failed and enters into the backoff state. That is, the $\mathbb{S}_t$ inflates the contention window according to the binary exponential backoff algorithm of CSMA/CA and then, chooses the backoff counter randomly within the window. Otherwise (if $\mathbb{S}_t$ and $\mathbb{S}_r$ exchange the RTS and CTS successfully), $\mathbb{S}_t$ can transmit a data packet without collisions with other SUs. Once $\mathbb{S}_r$ receives the data packet, it returns the ACK to notify the successful reception of the data packet. When $\mathbb{S}_t$ does not receive the ACK, it knows that the data transmission has failed, and enters

Algorithm 1. POST algorithm.

```
doFineSensing ← 1;
if (doFineSensing = 1) then
    execute fine sensing;
    if (channel is sensed 'idle') then
        continue transmission;
        doFineSensing ← 0;
    end-if
else
    execute fast sensing;
    if (channel is sensed 'idle') then
        continue transmission;
    else
        doFineSensing ← 1;
    end-if
end-if
if (data transmission fails) then
    doFineSensing ← 1;
end-if
```

into the backoff state with a new backoff counter. Once a packet transmission succeeds, the contention window returns to the initial size according to the standard CSMA/CA.

B. POST Algorithm

In Algorithm 1, we describe the POST algorithm that determines the type of spectrum sensing in the adaptive manner. Before we discuss the operation of POST, we first explain two kinds of spectrum sensing techniques.

In IEEE 802.22, MAC layer performs two different types of spectrum sensing techniques, i.e. fast sensing and fine sensing. In the fast sensing, a channel is sensed for a short interval less than 1ms, which is an energy detection using Welch's periodogram [5]. It is used to sense the signal availability of the channel quickly. However, it does not distinguish the PU's signal from the background noise. On the other hand, in the fine sensing, a channel is sensed for a long time around 25ms. It is used for the detailed examination of channels by exploiting the signal signatures. One of the representative methods is the cyclostationary feature detection [6]. The fine sensing can detect the PU's signal even in the low SNR environment. However, it has the serious drawback of the long sensing time. Hence, we need a hybrid sensing technique to compensate the shortcomings of the fast and fine sensing.

We propose the POST algorithm to resolve this issue. As described in Algorithm 1, an $\mathbb{S}_t$ is initialized to perform the fine sensing. If $\mathbb{S}_t$ finds that the channel is clear, it performs the fast sensing from the next time, regardless of the current sensing type. On the contrary, if $\mathbb{S}_t$ finds that the channel is not clear, it conducts the fine sensing next time. Hence, with the POST algorithm, the secondary users are conservative to be activated when there are active primary users. On the contrary, it is likely to remain active for a long time when the primary users are newly activated. To remedy this slow reaction, the secondary users set the sensing type as the fine sensing whenever the data transmission fails since it strongly suggests that the primary users are active.

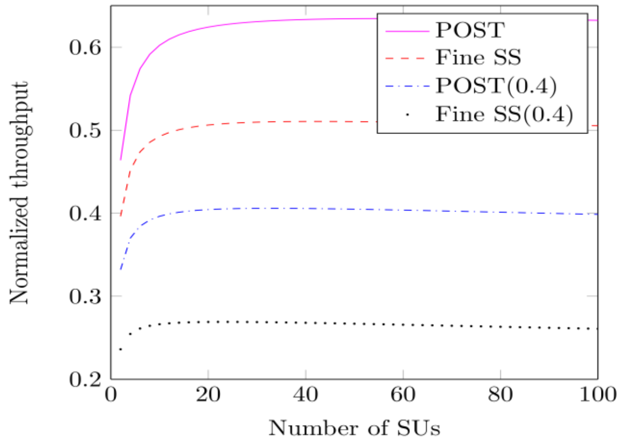

Figure 3. Normalized throughput of SUs vs number of SUs.

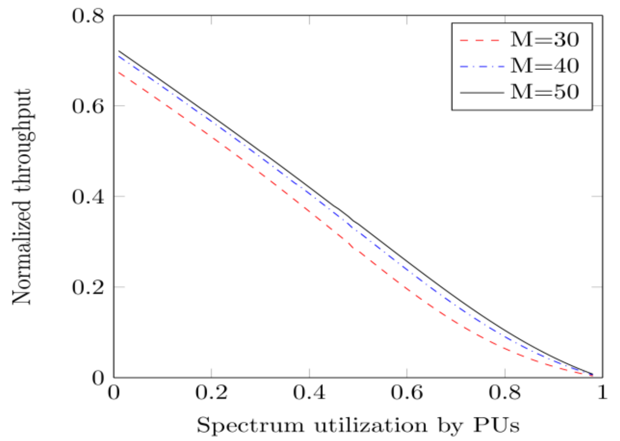

Figure 4. Normalized throughput of SUs vs activity of PUs.

IV. Numerical Results

We here discuss the analytical results on the performance of our proposed scheme. Table I summaries the system parameters used in the performance evaluation.

To evaluate the tradeoff between the sensing time and the throughput, we compare the performances of our proposed scheme with the POST algorithm and that with the fine sensing only, respectively. In Fig. 3, we provide the normalized throughput of the two schemes while increasing the number of SUs, where the PU activity rate is set to 0.1. We can see that the throughput curves monotonically increase with the number of SUs and enter into the saturated state. The gap between the throughput curves advocates the tradeoff between the sensing time and the throughput. We observe that the POST algorithm substantially improves the throughput by reducing the channel sensing time. We also consider the case of higher PU activity of 0.4 in Fig. 4. Under higher PU activity, the throughput of SUs decreases and the effect of the POST algorithm becomes more significant. Fig. 3 shows the effect of the PU activity on

Table 1. System parameters.

Parameter	Value
PHY header	120 bits
MAC header	272 bits
Packet payload	1024 Bytes
NTS	112 bits + PHY header
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Backoff retry limit	5
Min/MAx CW size	16/256
Fine/Fast sensing error	0.01/0.2
Fine/Fast sensing time	0.5/10.0 ms
SIFS time	10 μs
DIFS time	50 μs
Slot time	20 μs
Propagation delay	1 μs
Channel bit rate	1 Mbit/s

the normalized throughput of SUs. The throughput decreases monotonically with the activity of PUs, but it is not sensitive to the number of SUs.

V. CONCLUSION

We have proposed a MAC protocol with the adaptive spectrum sensing time for CR networks. Previous MAC protocols based on the carrier sensing are simple and efficient but they are not suitable for CR networks since the carrier sensing is reliable in the high SNR only. The spectrum sensing can compensate the carrier sensing in the low SNR regime with the cost of increased channel sensing time. Our approach provides a good balance between the sensing time and the throughput of SUs while guaranteeing the exclusive channel access of PUs. Numerical results show that our scheme significantly outperforms the standard CSMA/CA with the long spectrum sensing time.

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