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A Contention-Free Reporting Scheme Based MAC Protocol for Cooperative Spectrum Sensing in Cognitive Radio Networks

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ABSTRACT Cooperative spectrum sensing (CSS) is widely investigated in cognitive radio networks (CRNs) to improve the spectrum sensing performance. To realize CSS, how to collect sensing data from the secondary users (SUs) is one of the major problems. To solve the problem, in this paper, we propose a contention-free reporting scheme-based MAC protocol for CSS in the CRNs. With the proposed the MAC protocol, the SUs can report the sensing data to the fusion center without any reporting collisions, therefore increasing the reporting channel efficiency. Moreover, two admission control schemes are designed for throughput optimization and energy efficiency optimization, which further improve the performance of the proposed MAC protocol. Simulation results show that the proposed MAC protocol outperforms existing protocols.

INDEX TERMS Cognitive radio, cooperative spectrum sensing, MAC protocol, contention-free reporting, admission control, throughput, energy efficiency.

I. INTRODUCTION

Cognitive radio (CR) technology has been proven to be an effective way to enable dynamic spectrum access (DSA) to the unused licensed channels for improving spectrum utilization efficiency [1]. Spectrum sensing is a crucial function in CR, which enables the secondary users (SUs) to detect the presence or absence of primary user (PU) and to decide whether the given licensed channel can be used in a given time or not [2]. To further improve the sensing performance and handle the well-known hidden terminal problem, cooperative spectrum sensing (CSS) is proposed to collect the local sensing results from multiple SUs to a fusion centre (FC) and a global decision is made according to some specific fusion rules (i.e. hard combination or soft combination) to infer the absence or presence of PU [3], [4].

The basic functions of CSS include three phases: local sensing, reporting and data transmission. Recently, a practical problem in realizing CSS has drawn much attention [5]: how to realize the reporting phase, in another word, how to collect the local sensing results. To solve this problem, two basic issues must be considered: the first one is to build the reporting wireless channel between the SUs and FC, the second one is to handle the multiple access problem while the SUs sharing the reporting channel (RCH). For the first issue, most of the previous works assume that there are dedicated reporting channels (DRCHs) between SUs and FC [5]–[12]. Other works use the sensed idle licensed channels to report the sensing results [13], [14], which may cause additional interference to PUs during the reporting phase. In this paper, we focus on the DRCH based reporting protocol design. For the second issue, a media access control (MAC) protocol is needed. The related access protocols can be classified into three categories: fixed TDMA [6], [7], [11], hybrid access [8], [9], and random access [5], [10], [12]. In [6], [7], and [11], the reporting phase is divided into multiple slots and preassigned to the SUs according to a predefined number. The fixed slot assignment scheduling can not meet the network size (the number of SUs) change with time. In [8] and [9], the reporting phase is divided into two stages: dedicated reporting stage and contention-based reporting stage. TDMA is used in the first stage, and random access is used in the second stage to form a hybrid access. However, multiple DRCHs are assumed in [8] and [9], which may cause a large spectrum resource overhead. Considering the random access based protocols, [5] presents an adaptive random access reporting schemes where the number of reporting slots is set by solving an finite-horizon decision problem. In [10], a CSMA/CA like random reporting access is used in the reporting phase.

In [12], two random access reporting protocols: slotted-Aloha (S-ALOHA) and reserved-Aloha (R-ALOHA) based reporting protocol are proposed. Moreover, the capture effect is also considered while analyzing the random access process [12]. However, the inevitable collision nature (two or more SUs report in the same reporting slot) of the random access protocols may decrease the sensing performance . Moreover, as the sensing results are reported after the sensing phase, the reporting collisions may also cause a spectrum sensing energy waste and decrease the energy efficiency of CSS. Hence, a new reporting protocol is needed here to handle the reporting collision problem.

To solve both the poor scalability problem of fixed TDMA protocols and the reporting collision problem of random access protocols, we design a new MAC protocol with a two-step hybrid reporting access scheme to enable contention-free reporting and dynamical reporting slot reassignment. The proposed MAC protocol is named as contention-free MAC protocol (CF-MAC). In the CF-MAC protocol, the SUs firstly join a slotted Aloha process before joining the CSS process. After that, the winners will be scheduled with dedicated reporting slots by the FC. Then, the winners will report the sensing results in a contention-free manner in the following MAC frames. If any assigned reporting slot is out of usage, the slot will be dynamically reassigned by the FC.

The contributions of the proposed CF-MAC protocol include: i) Contention-free reporting is realized, which may improve the sensing and throughput performance, and decrease the sensing energy waste. ii) It can adapt to different network size by hybrid reporting access scheme and reporting slot reassignment scheme. iii) It enables the FC controlling the admission of the SUs according to the optimization results for different performance metrics, which further improve the MAC protocol performance.

Numerical results show that comparing to the nowadays protocols, the proposed CF-MAC can achieve a better sensing performance and higher throughput. Moreover, although there are some additional MAC phases in the CF-MAC which increase the control overhead, CF-MAC gets a good energy efficiency performance thanks to the efficient contention-free reporting scheme. Furthermore, the performance of the CF-MAC can be further improved by selecting the optimal number of CSS nodes according to the throughput metric or energy efficiency metric.

This paper is organized as follows: system model and protocol overview is shown in Section II. Section III shows the details about the proposed MAC operations. Performance analysis of the proposed MAC protocol is drawn in Section IV. Simulation results are presented in Section IV and the conclusions are drawn in the last Section.

II. SYSTEM MODEL AND PROTOCOL OVERVIEW

With M SUs and a FC, we consider a CRN which is shown in Fig. 1. It is assumed that there is a DRCH and a data channel (DCH) in the CRN [15]. The DRCH is dedicated to the SUs and FC, which is free from the interference of PUs. Considering that, using a dedicated channel for control messages exchange is a widely accepted assumption in CRN [5], [8], [9], [12], [15]. Each SU attempts to detect the presence of the PUs on the DCH by individual sensing and then sends the individual sensing results to the FC through the DRCH. We assume each SU has identical individual detection probability P_d and false alarm probability P_f [12], [16], [17]. It is assumed that hard fusion rule is used by the FC to make the final decision. Nevertheless, soft fusion rule is also applicable with the proposed MAC protocol.

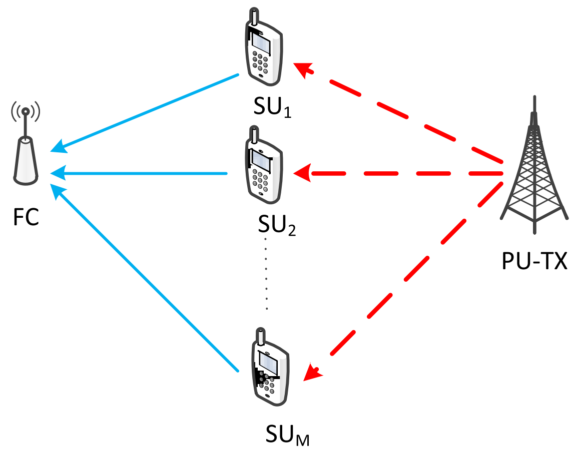

FIGURE 1. System model.

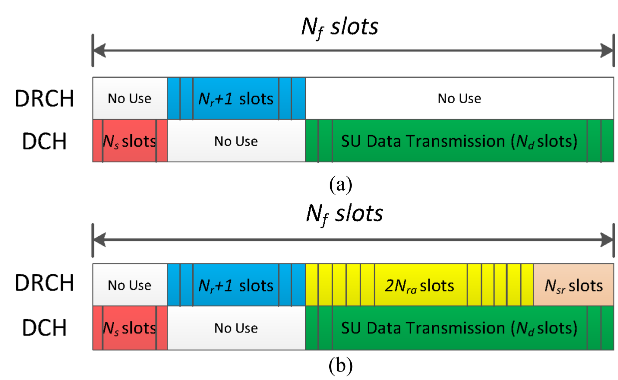

FIGURE 2. MAC frame structure of the traditional MAC protocol and the proposed MAC protocol. (a) The operation of the traditional MAC protocol. (b) The operation of the proposed MAC protocol.

Fig. 2 shows the frame structure comparison of the proposed MAC and the traditional one. There are three traditional phase for CSS as [5], [12] in the proposed MAC frame structure: sensing phase (N_s slots), reporting phase ($N_r + 1$ slots) and data transmission phase (N_d slots). There are totally $N_f = N_s + N_r + 1 + N_d$ slots in a MAC frame. Besides, two new phases: reporting access phase ($2N_{ra}$ slots, which equal to N_{ra} accessing slots) and slot reassignment phase (N_{sr} slots), are added to the RCH to solve the collision problem of the multiple access reporting and the inefficient problem of the traditional TDMA based reporting.

Through the reporting access phase, each newly joining SU tries to reserve the reporting slot in the next MAC frame. Therefore, a contention-free reporting protocol is realized without any reporting collision. A report access ready to send (RARTS)/report access clear to send (RACTS) handshake scheme is used in the reporting access phase. Therefore, the length of an access slot equals two slots. To adapt to the dynamic network when the number of SUs changes, the idle reporting slot will be reassigned through the slot reassignment phase. That is to say, if any assigned reporting slot remain idle for a given number of MAC frames, it will be reassigned to other SUs by the FC. Therefore, the efficiency of the reporting phase is maintained. Moreover, as we focus on the cooperative sensing reporting problem in this paper, we assume that N_s is fixed and long enough to achieve good sensing performance. As N_r is changed according to the number of reporting SUs, for convenience of performance analysis, we set $K = N_r + 1 + N_d$, $L = N_f - N_s - N_{sr}$ and $L > M$. The details of the proposed MAC protocol are shown in the following section.

III. THE PROPOSED MAC PROTOCOL OPERATION

A. NETWORK INITIALIZATION

In the first MAC frame of the CRN, as no SU win any reporting slot, the whole MAC frame will be set as an initial reporting access phase with $\lfloor \frac{N_f}{2} \rfloor$ slots. Any SU which wants to join the CRN and CSS process can randomly choose a slot in a slotted ALOHA manner and send a RARTS in the chosen slot. If a slot is chosen by only one SU, the RARTS will be successful sent to FC and FC will reply a RACTS. The RACTS includes the index of reporting slot which can be used by the SU in the following MAC frames. If a RACTS is received by a SU successfully, the SU will join the CSS process in the next MAC frame. We name the SUs which will join the CSS process as SSU (sensing SU) for short.

B. SENSING PHASE

To maintain the contention-free reporting and save the sensing power consumption, only the SSUs can join the sensing phase. It is assumed that the sensing phase has a fixed time duration which is long enough to achieve an identical P_d and P_f for each SSU. Moreover, energy detector [18] is used by each SSU.

C. REPORTING PHASE

After getting the local sensing result in the sensing phase, each SSU picks the reporting slot which it is assigned in the former MAC frames, and then sends the local decision result. As the reporting slots are assigned by the FC in a sequential manner, a contention-free reporting process is realized. After gathering all of the local decision reports, according to k-out-of-N fusion rule [16], FC broadcasts a final decision in the end of the reporting phase. Moreover, if PU is detected absent in the final decision, FC will broadcast a spectrum assign frame to the SSUs based on Round-Robin scheduling.

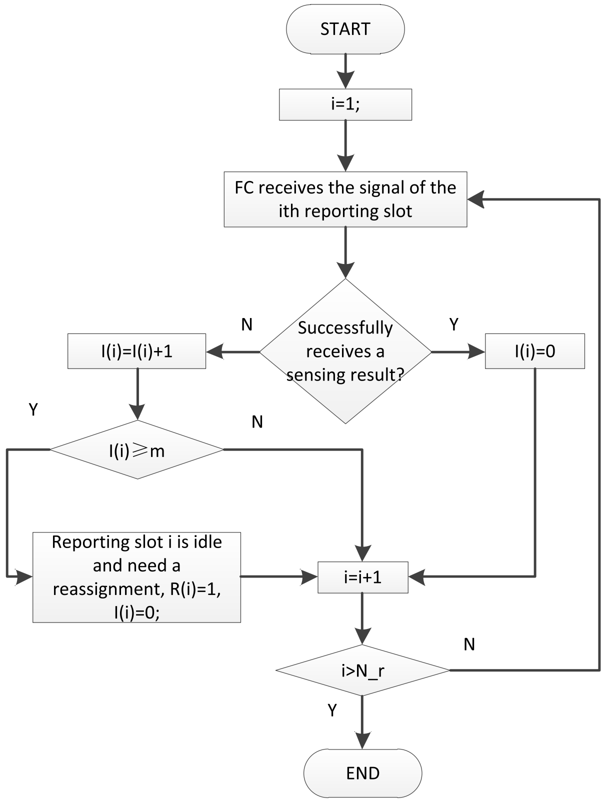

FIGURE 3. **Algorithm 1: Idle reporting slots identifying.**

D. DATA TRANSMISSION PHASE

The SSU, which has received a spectrum assign frame in the end of the reporting phase, will switch to the PU channel and transmit data packet during the data transmission phase.

E. REPORTING ACCESS PHASE

The reporting access phase is designed to handle the newly joining SUs. The number of reporting access slots will be broadcasted by the FC in the beginning of reporting access phase. After that, all the SUs which want to join the CSS and begin data transmission process in the next MAC frame will randomly choose a reporting access slot in a slotted ALOHA manner and send a RARTS in the chosen reporting access slots. As mentioned before in network initialization, the SUs which have successfully received a RACTS will become SSU and join the CSS process in the following MAC frames. Considering that, the admission control scheme can be easily realized in this phase by setting the number of reporting access slots as zero when no more SUs are allowed to access.

F. SLOT REASSIGNMENT PHASE

To solve the problem of the traditional TDMA protocol, the assigned reporting slots which are out of usage can be reassigned by the FC in this phase. An assigned reporting slot will be out of usage for the following reasons: the SSU is power off; the SSU has left the coverage of the CRN; the SSU has finished data transmission and has no new data to send. The slot reassignment process includes two

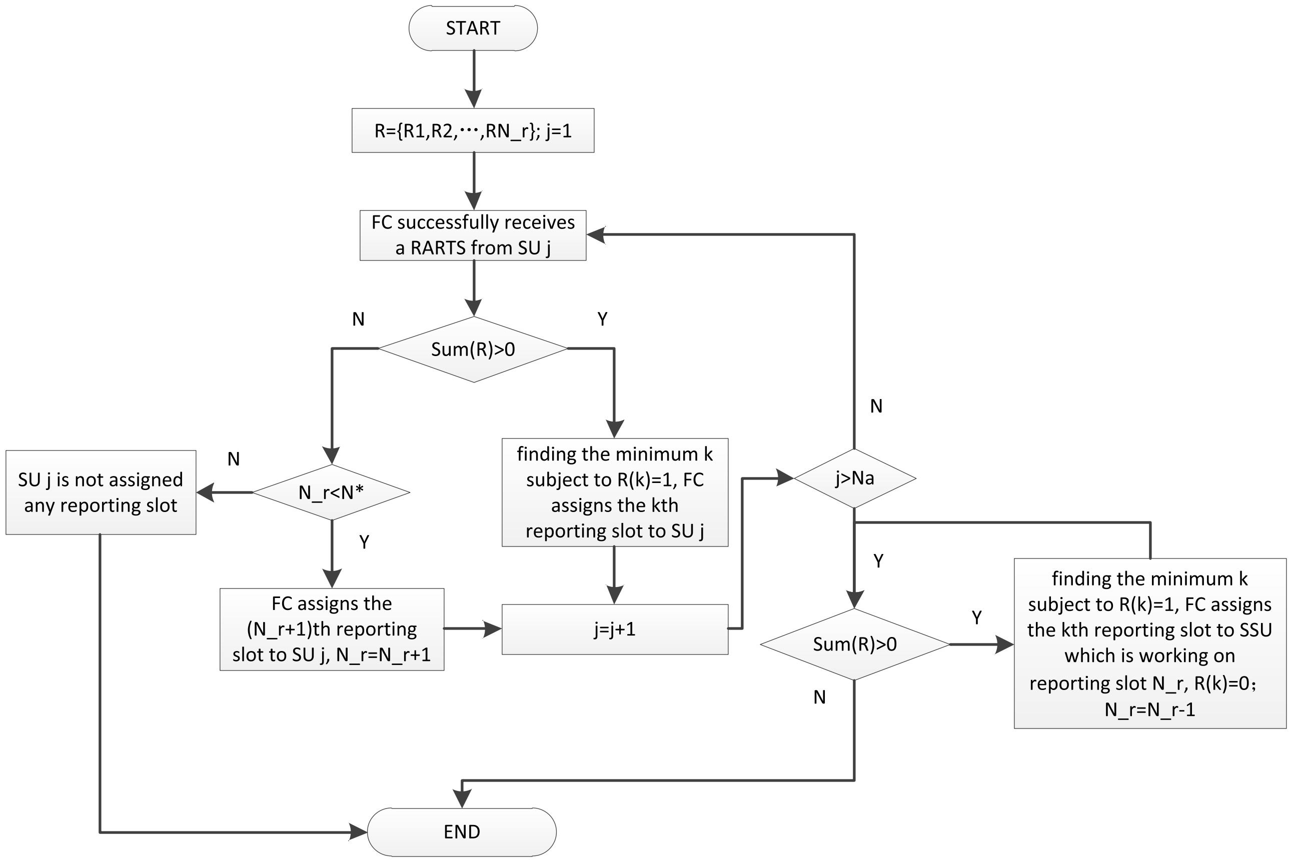

FIGURE 4. **Algorithm 2: Idle reporting slots reassignment.**

steps: Step 1, to decide whether an assigned reporting slot is idle; Step 2, to reassign the idle reporting slots. To Step 1, we design an simple rule to decide the idle reporting slots: if an assigned reporting slot remains idle in the consecutive m MAC frames, it is considered as an idle reporting slot where m is a design parameter. We denote I and R as the idle reporting slots identifying set and indicator set of the idle reporting slots, respectively. The flow diagram of Step 1 is shown in **Algorithm 1**. To Step 2, firstly, the idle assigned reporting slots will be assigned to the newly joining SUs in the reporting access phase. If there are still idle assigned report slots remaining with no newly joining SUs to assign, these idle report slots will be reassigned by the FC to the SSU which has the largest reporting slot index one by one. Therefore, the assigned report slot with the largest index will not be used for reporting and the number of assigned reporting slots will be minimized, which leaves more time duration for data transmission phase. The flow diagram of Step 2 is shown in **Algorithm 2**.

IV. PERFORMANCE ANALYSIS

A. REPORTING ACCESS PROCESS ANALYSIS

As the reporting access process can influence both the number of cooperative sensing nodes and the spectrum sensing performance, we analyze the reporting access process at first. As mentioned in Section 2, to reserve the reporting slot in the following MAC frames, SUs join the reporting access process by choosing one of the N_{ra} accessing slots randomly through a frame slotted ALOHA manner [19]. As N_{ra} is influenced by the number of reserved reporting slots, if j reporting slots have been reserved in the current MAC frame, we have:

$$N_{ra}(j) = \lfloor \frac{L-j}{2} \rfloor \tag{1}$$

Different to [12], as there is a slot reassignment phase in the proposed MAC protocol, SUs do not need to release the reserved reporting slot periodically, which saves the overhead of periodically reporting access. For analytical simplicity, we assume the winners of the reporting access process will keep doing the cooperative sensing task without leaving the CRN. Then, we use a discrete Markov chain model to analyze the reporting access process in a long time scale with plenty of MAC frames. Denote n_j^i as the state of the reporting access process, where n_j^i is the number of SUs joining the reporting access process in the ith MAC frame when there are j reporting slots are reserved. We have $n_j^i = M - j$. According to [12], the probability that only one SU selects one specific slot among the $N_{ra}(j)$ slots is:

$$P_{s,j} = \frac{n_j^i (N_{ra}(j) - 1)^{n_j^i - 1}}{N_{ra}(j)^{n_j^i}} \tag{2}$$

Then, we denote the initial state row vector of the reporting access process as $u1 = [n_0^1, n_1^1, \ldots, n_M^1]$. According to the theory of Markov chain [20], we denote the transition matrix as $U \in R^{(M+1)(M+1)}$. Then, the transition probability of state n_j^i to state n_k^{i+1} is denoted by $U_{j+1,k+1}$. We have:

$$U_{j+1,k+1} = \begin{cases} \binom{N_{ra}(j)}{k-j} P_{s,j}^{k-j}(1-P_{s,j})^{N_{ra}(j)-(k-j)}, & k \geq j, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

According to (3), we have:

$$U_{M+1,k+1} = \begin{cases} 1, & k = M, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Besides, if $j \neq M$, we have $U_{j+1,M+1} = \binom{N_{ra}(j)}{M-j} P_{s,j}^{M-j}$ $(1-P_{s,j})^{N_{ra}(j)-(M-j)} > 0$. According to [21], the reporting access process is an absorbing Markov process with a absorbing state: $U_{M+1,M+1} = 1$. As the reporting access process is analyzed in a long time scale, if the absorbing state is reached after the kth MAC frame, we have the steady number of SUs joining reporting access as: $n_M^k = M - M = 0$. Then, the steady number of reporting SUs is $\overline{N_r} = M$. Considering the admission control scheme which will be discussed later, if the maximum reporting SUs is set as $N^* < M$, we have:

$$U_{N^*+1,k+1} = \begin{cases} 1, & k = N^*, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

The steady number of reporting SUs will be changed to $\overline{N_r} = N^*$.

B. SPECTRUM SENSING ANALYSIS

During the sensing phase, considering the steady state is achieved, there are $\overline{N_r}$ SUs performing spectrum sensing to detect the PU signals. There are two PU states: present and absent. Denote Q_d and Q_f as the global detection probability and global false alarm probability, respectively, we use the k-out-of-N fusion rule and have:

$$Q_d(\overline{N_r}, T) = \sum_{l=T}^{\overline{N_r}} \binom{\overline{N_r}}{l} P_d^l (1-P_d)^{\overline{N_r}-l} \tag{6}$$

$$Q_f(\overline{N_r}, T) = \sum_{l=T}^{\overline{N_r}} \binom{\overline{N_r}}{l} P_f^l (1-P_f)^{\overline{N_r}-l} \tag{7}$$

where T is the decision threshold of the k-out-of-N fusion rule.

C. THROUGHPUT AND ENERGY EFFICIENCY ANALYSIS

1) THROUGHPUT

According to (6) and (7), the average throughput can be expressed as:

$$R(\overline{N_r}, T) = \frac{c_0(1-Q_f(\overline{N_r}, T))(K-\overline{N_r})P_0}{K} + \frac{c_1(1-Q_d(\overline{N_r}, T))(K-\overline{N_r})P_1}{K} \tag{8}$$

where P_0 and P_1 are the average probability for DCH to be free and busy, respectively. c_0 is the average rate of a SU without interference while c_1 is the average rate of a SU with PU interference.

2) ENERGY EFFICIENCY

The power consumption of the ith MAC frame can be expressed as follows:

$$E_{tot}(i) = N_r^i E_s + N_r^i E_r + P_{free}E_t + (M - N_r^i)E_a + N_{sr}E_{sr} \tag{9}$$

where $E_s = P_s t_s$ and $E_r = P_r t_r$ are the power consumption of one SSU during the sensing phase and reporting phase, $E_t = P_t t_{tr}$ is the power consumption of the chosen SSU during the transmission phase, $E_a = P_r t_r$ and $E_{sr} = P_r t_r$ are the power consumption of one SU during the reporting access phase and slot reassignment phase. As mentioned above, reporting access process is an absorbing Markov process, the average power consumption under absorbing state can be approximately expressed as:

$$\overline{E_{tot}} \approx \overline{N_r}E_s + \overline{N_r}E_r + P_{free}E_t \tag{10}$$

Then, the average energy efficiency (EE) can be expressed as [22]

$$\eta(\overline{N_r}, T) = \frac{R(\overline{N_r}, T)}{\overline{E_{tot}}} \tag{11}$$

D. OPTIMAL NUMBER OF COOPERATIVE SPECTRUM SENSING NODES AND ADMISSION CONTROL

Adding more reporting SUs can improve the sensing accuracy. However, more reporting slots decrease the time duration for data transmission. Therefore, there is a tradeoff between the reporting phase and the data transmission phase. To further improve the system performance, we design the following two optimization problems according to different design criteria.

1) THROUGHPUT MAXIMIZATION

The optimal problem is expressed as follows.

$$\begin{aligned} \max_{N_r,T}\ R = & \frac{c_0(1-Q_f(N_r,T))(K-N_r)P_0}{K} \\ & + \frac{c_1(1-Q_d(N_r,T))(K-N_r)P_1}{K} \\ \text{s.t. } & Q_d(N_r,T) \geq \Gamma \\ & 1 \leq N_r \leq M \\ & 1 \leq T \leq N_r, \quad \forall N_r,\ T \in N^+ \end{aligned} \tag{12}$$

where Γ is the required cooperative detection probability threshold.

2) ENERGY EFFICIENCY MAXIMIZATION

The optimal problem is expressed as follows.

$$\begin{aligned} \max_{N_r,T}\ & \eta = \frac{R}{E_{tot}} \\ \text{s.t. } & Q_d(N_r,T) \geq \Gamma \\ & 1 \leq N_r \leq M \\ & 1 \leq T \leq N_r, \quad \forall N_r,\ T \in N^+ \end{aligned} \tag{13}$$

Since both N_r and T are bounded, we can utilize a two-dimensional extensive search algorithm to solve the problems in (12) and (13). After that, we can set the upper bound for the maximum number of reporting SUs according to the optimal results of (12) or (13). With the upper bound, admission control can be easily realized by FC in the reporting access phase.

V. NUMERICAL RESULTS

In this section, we provide numerical results to compare our proposed CF-MAC protocols with several extant protocols. Notice that our proposed protocols are characterized with contention-free as well as dynamic admission control in reporting phase. Considering the admission control scheme, we may divide the proposed protocols into CF-MAC with throughput optimization (CF-MAC-T) and CF-MAC with EE optimization (CF-MAC-EE). To the best of our knowledge, there are no other extant protocols which have the exactly same characteristics as CF-MAC-T and CF-MAC-EE. We take S-ALOHA and R-ALOHA [12] as comparison, since they are two state-of-the-art MAC protocols designed for the same system settings as our protocols. However, we should note that both S-ALOHA and R-ALOHA adopt contention scheme. Therefore, for extensive comparison, we also consider the protocols proposed in [6], [7], and [11] which are contention-free but use a predefined number of reporting slots (i.e., without dynamic admission control). We use CF-MAC-N to represent these protocols. By comparing CF-MAC-T/-EE with CF-MAC-N, we may verify the significance and effectiveness brought by adopting dynamic admission control scheme. A summary on all the compared protocols is given in Table 1.

TABLE 1. Summary of the compared protocols.

Protocol	Reporting Scheme	Reporting Phase Design
S-ALOHA [12]	contention	fixed without admission control
R-ALOHA [12]	contention	fixed without admission control
the proposed CF-MAC-T	contention-free	dynamic with admission control
the proposed CF-MAC-EE	contention-free	dynamic with admission control
CF-MAC-N	contention-free	predefined without admission control

As in [12], the length of the reporting phase of S-ALOHA and R-ALOHA is set as 25 contention slots. The general simulation parameters are set as follows: $P_d = 0.7, P_f = 0.3$, $\Gamma = 0.9, P_0 = 0.9, P_1 = 0.1, N_f = 400, N_s = 40, N_{sr} = 20$, $t_s = t_r = 0.01s$, $c_0 = 2Mb/s$, $c_1 = 0.2Mb/s$. The power consumption parameters are set as [23]: $P_s = 0.01w$, $P_r = P_t = 0.1w$. The list of all simulation settings can be seen in Table 2. Under these simulation settings, the optimized values of (12) are N_r=5 and T=2 and those of (13) are N_r=17 and T=9. Moreover, we assume all the SUs join the cooperative spectrum sensing process in each MAC frame unless stated otherwise. For each set of parameter values, simulation results are obtained with running 10000 MAC cycles.

TABLE 2. Simulation parameters.

Parameter	Value
P_d	0.7
P_f	0.3
Γ	0.9
P_0	0.9
P_1	0.1
N_f	400
N_s	40
N_{sr}	20
t_s	0.01s
t_r	0.01s
P_s	0.01w
P_r	0.1w
P_t	0.1w
c_0	2 Mbps
c_1	0.2 Mbps

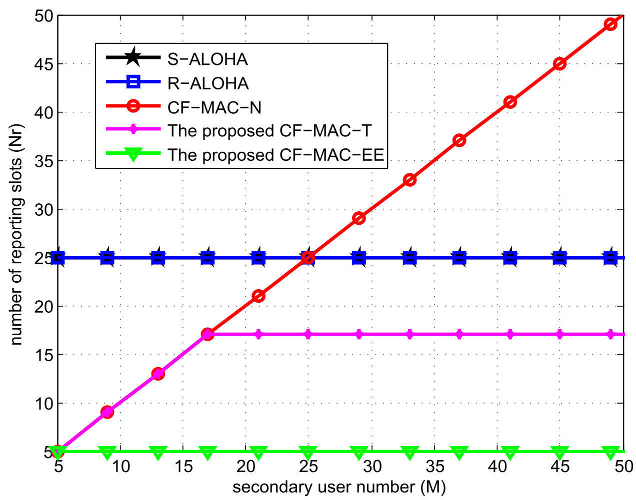

FIGURE 5. Number of reporting slots (N_r) versus the number of contending SUs (M).

The cooperative sensing reporting related metrics are shown in Fig. 5 to Fig. 7. In Fig. 5, we investigate the length of the reporting phase against the number of contending SUs (M). Unlike S-ALOHA and R-ALOHA which use fixed length for the reporting phase, we can see the N_r of the proposed CF-MAC protocols increase with the increasing M. The maximal N_r of CF-MAC-T and CF-MAC-EE are limited by the admission control scheme. The maximal N_r of CF-MAC-N is predefined as M.

Fig. 6 shows the nature of successful reporting SUs with varying number of contending SUs. As the proposed CF-MAC protocols are contention-free, the number of successful reporting SUs are highly related to the number of reporting slots which are shown in Fig. 5. We can see the number of successful reporting SUs of CF-MAC-T and CF-MAC-EE are limited by the admission control scheme, while that of CF-MAC-N increases with the increasing M.

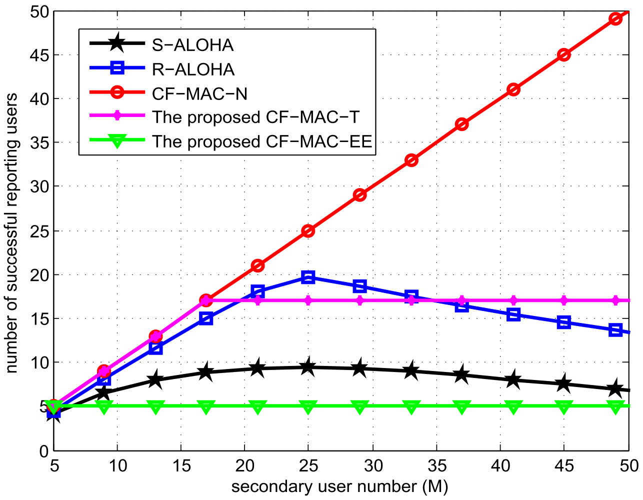

FIGURE 6. Number of successful reporting users versus the number of contending SUs (*M*).

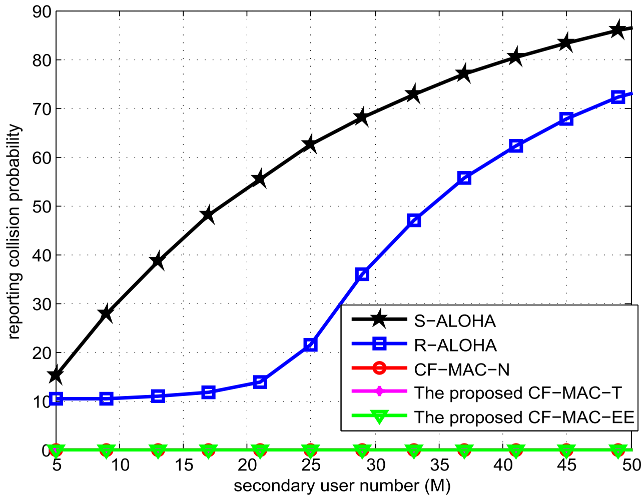

FIGURE 7. Reporting collision probability versus the number of contending SUs (*M*).

To S-ALOHA and R-ALOHA, due to the nature of random access, the number of successful reporting SUs are highly related to the number of contending SUs. We can see that, with an increasing M, the number of successful reporting SUs of S-ALOHA and R-ALOHA increases first, reaches a maximum and then starts decreasing. The maximum number of successful reporting SUs is reached when M has the same number as the reporting SUs. Further increase of M negatively affects the number of successful reporting SUs as the reporting collision probability becomes much higher. Moreover, we can see the number of successful reporting SUs of CF-MAC-T is lower than that of R-ALOHA while the number of successful reporting SUs of CF-MAC-EE is lower than that of S-ALOHA. This is because in CF-MAC-T, a tradeoff between sensing performance and reporting overhead is made for throughput maximization; in CF-MAC-EE, a tradeoff between sensing performance and reporting overhead is made for energy efficiency maximization.

The nature of reporting collision probability is depicted in Fig. 7. We can see that reporting collision probability remain zero for all the contention-free protocols. Moreover, we can see the reporting collision probability of S-ALOHA and R-ALOHA increase with increasing M. This is because N_r remains stable in S-ALOHA and R-ALOHA with increasing M that more contending SUs bring more reporting collisions.

The MAC related metrics with analytical and simulation results are shown in Fig. 8 to Fig. 10. Fig. 8 presents the cooperative false alarm (Q_f) versus the number of SUs (M) with the required cooperative detection probability $\Gamma = 0.9$. From Fig. 8, we can see that CF-MAC-N gets a much lower Q_f than the other four when M is large. However, this performance is achieved by the cost of more reporting slots overhead, which can be seen in Fig. 5. Moreover, with much lower reporting slots overhead which can be seen in Fig.5, from Fig. 8, we can see CF-MAC-T gets a similar Q_f as that

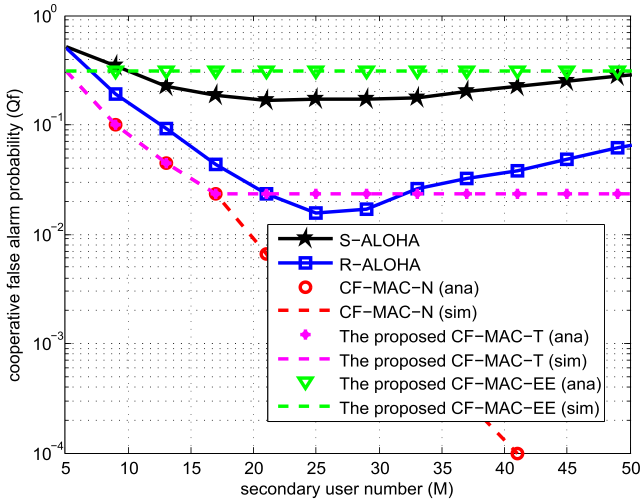

FIGURE 8. Cooperative false alarm probability (Q_f) versus the number of contending SUs (*M*).

of R-ALOHA and CF-MAC-EE gets a similar Q_f as that of S-ALOHA. This is because using much less reporting slots to achieve good enough sensing performance in CF-MAC-T and CF-MAC-EE, more time is left for data transmission to improve throughput performance and energy efficiency performance, which proves the sensing efficiency of the dynamic contention-free reporting protocols.

In Fig. 9, we plot the expected throughput versus the number of SUs (M). As shown in Fig. 9, CF-MAC-T gets the optimal throughput compared with the others. Moreover, CF-MAC-EE gets a similar throughput like S-ALOHA, which shows the tradeoff of throughput and energy efficiency. Furthermore, we can see the throughput of S-ALOHA and R-ALOHA decrease when M is high ($M > 25$). This is due to the reporting collision problem of S-ALOHA and R-ALOHA when M is high. One can also observe that throughput of CF-MAC-N decreases sharply when $M > 20$. This is because

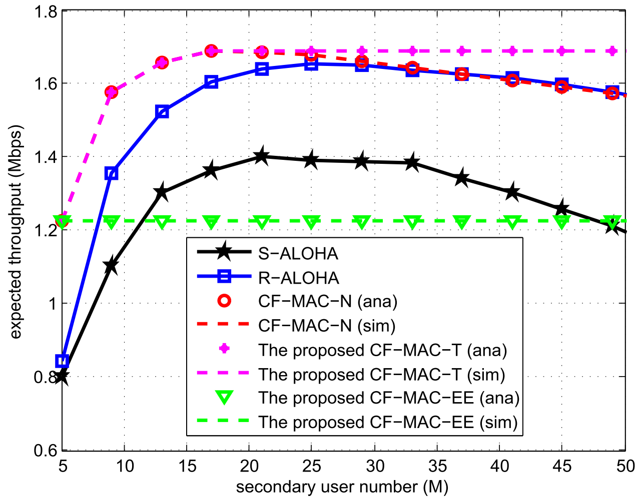

FIGURE 9. **Average throughput (R) versus the number of contending SUs (N).**

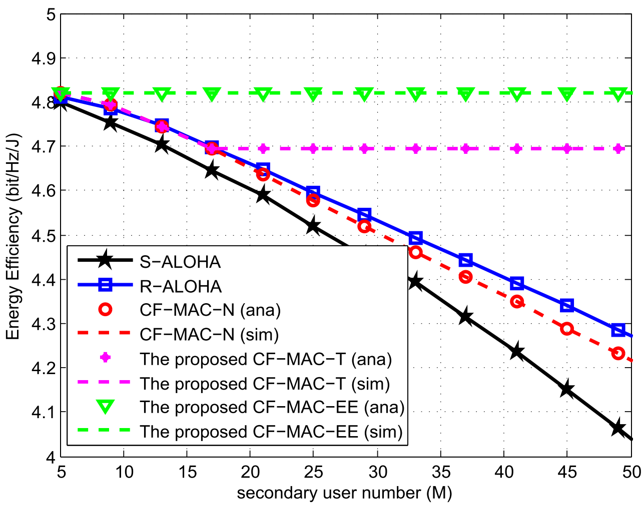

FIGURE 10. **Energy efficiency (η) versus the number of contending SUs (N).**

without optimization and admission control, the reporting slots overhead grows rapidly with increasing M and fewer slots can be used for data transmission.

Fig. 10 shows the energy efficiency versus the number of SUs (M). As expected, CF-MAC-EE gets the optimal energy efficiency. In addition, we can see CF-MAC-T gets the second best energy efficiency among the five protocols. The above results prove that admission control is very important for energy efficiency metric of the contention-free reporting protocols.

To evaluate **Algorithm 1** and **Algorithm 2** of the slot reassignment phase in all the three proposed CF-MAC protocols, we assume that each SU tries to access the reporting phase with various probability P1 and each SSU stops reporting in its reserved reporting slot with various probability P2 in each MAC frame. Fig. 11 shows the simulation result. We can see the proposed CF-MAC-T and CF-MAC-EE still achieve

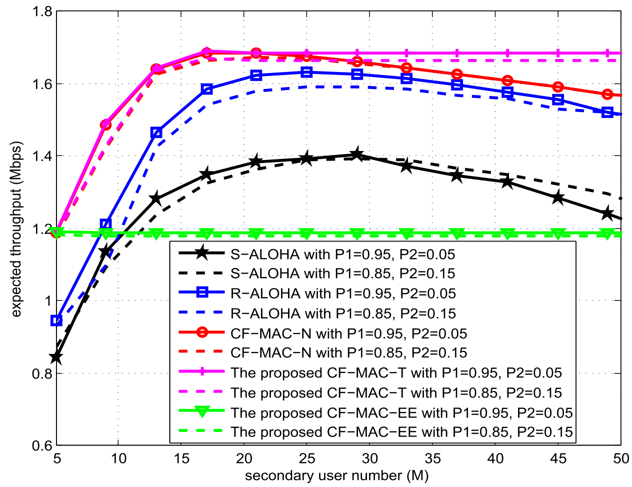

FIGURE 11. **Evaluation of the slot reassignment related algorithms.**

good throughput performance, which demonstrates the effectiveness of **Algorithm 1** and **Algorithm 2**. Moreover, with P1=0.95 and P2=0.05, as the reserved reporting slots are used more efficiently, we can see that both CF-MAC-T and CF-MAC-EE achieve higher network throughputs than those with P1=0.85 and P2=0.15.

VI. CONCLUSION

In this paper, we have proposed a contention-free reporting scheme based MAC protocol for CSS in CRNs. The contention-free reporting scheme is realized by a two-step hybrid reporting access process without adding any new hardwares or spectrum resources. To further improve the reporting efficiency, two admission control schemes for different performance metrics have been proposed, which can be easily realized in the proposed MAC protocol. Both the cooperative spectrum sensing reporting metrics and MAC metrics have been shown in the simulation results to evaluate the effectiveness of the proposed MAC protocol.

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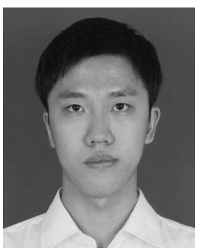

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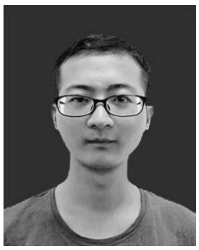

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