

An Efficient MAC Protocol With Selective Grouping and Cooperative Sensing in Cognitive Radio Networks

Yi Liu, Shengli Xie, *Senior Member, IEEE*, Rong Yu, *Member, IEEE*, Yan Zhang, *Senior Member, IEEE*, and Chau Yuen, *Senior Member, IEEE*

Abstract—In cognitive radio (CR) networks, spectrum sensing is a crucial technique for discovering spectrum opportunities for secondary users (SUs). The quality of spectrum sensing is evaluated by both sensing accuracy and sensing efficiency. Here, sensing accuracy is represented by the false-alarm probability and the detection probability, whereas sensing efficiency is represented by the sensing overhead and network throughput. In this paper, we propose a group-based cooperative medium access control (MAC) protocol called GC-MAC, which addresses the tradeoff between sensing accuracy and efficiency. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel while SUs in the same team perform the joint detection on the targeted channel. The sensing process will not stop unless an available channel is discovered. To reduce the sensing overhead, an SU-selecting algorithm is presented to choose selectively the cooperative SUs based on the channel dynamics and usage patterns. Then, an analytical model is built to study the sensing accuracy–efficiency tradeoff under two types of channel conditions: a time-invariant channel and a time-varying channel. An optimization problem that maximizes achievable throughput is formulated to optimize the important design parameters. Both saturation and nonsaturation situations are investigated with respect to throughput and sensing overhead. Simulation results indicate that the proposed protocol is able to significantly decrease sensing overhead and increase network throughput with guaranteed sensing accuracy.

Index Terms—Cognitive medium access control (MAC), sensing accuracy, sensing efficiency, spectrum sensing.

I. INTRODUCTION

RECENTLY, the explosive increase in wireless devices and applications has posed a serious problem of the

Manuscript received September 10, 2012; revised January 16, 2013 and March 18, 2013; accepted April 6, 2013. Date of publication April 18, 2013; date of current version October 12, 2013. This work was supported in part by the National Natural Science Foundation of China under Grant U1035001, Grant U1201253, and Grant 61273192; by the Research Council of Norway under Project 217006/E20; by the European Commission COST Action under Grant IC0902, Grant IC0905, and Grant IC1004; by the European Commission Seventh Framework Programme through Project EVANS under Grant 2010-269323; and by the International Design Center under Grant IDG31100102 and Grant IDD11100101. The review of this paper was coordinated by Prof. J. Deng.

Y. Liu is with Guangdong University of Technology, Guangzhou 510006, China, and also with Singapore University of Technology and Design, Singapore 138682 (e-mail: liuyi5115@yahoo.com.cn).

S. Xie and R. Yu are with Guangdong University of Technology, Guangzhou 510006, China (e-mail: shlxie@gdut.edu.cn; yurong@ieee.org).

Y. Zhang is with Simula Research Laboratory, Lysaker 1325, Norway (e-mail: yanzhang@simula.no).

C. Yuen is with Singapore University of Technology and Design, Singapore 138682 (e-mail: yuenchau@sutd.edu.sg).

Digital Object Identifier 10.1109/TVT.2013.2258952

compelling need of numerous radio spectra. The problem is greatly caused by the current fixed frequency-allocation policy, which allocates a fixed frequency band to a specific wireless system. However, a recent report published by the Federal Communications Commission (FCC) has revealed that most of the licensed spectrum is rarely utilized continuously across time and space [1]. To address spectrum scarcity and spectrum underutilization, cognitive radio (CR) has been proposed to effectively utilize the spectrum [2]–[4]. In CR networks, the secondary (unlicensed) users (SUs) are allowed to operate opportunistically in the frequency bands originally allocated to the primary (licensed) users (PUs) when the bands are not occupied by PUs. SUs are capable of sensing unused bands and adjust transmission parameters accordingly, which makes CR an excellent candidate technology for improving spectrum utilization.

Spectrum sensing is a fundamental technology for SUs to efficiently and accurately detect PUs to avoid interference to primary networks. However, in CR networks, many unreliable conditions [6]–[8], such as channel uncertainty, noise uncertainty, and no knowledge of primary signals, will degrade the performance of spectrum sensing. Cooperative sensing [9]–[15], has been extensively studied as a promising alternative to improving sensing performance at both the physical level and the medium access control (MAC) level. The main interest of this paper is the cooperative sensing mechanism at the MAC level, which performs sensing operations in two aspects: 1) assign multiple SUs to sense a single channel for improving the sensing accuracy; and 2) assign cooperative SUs to search for available spectrums in parallel to enhance sensing efficiency.

The improvement of sensing accuracy is extensively treated in [10]–[12]. The study in [10] reports a cooperative sensing approach through multiuser cooperation and evaluates the sensing accuracy. The authors of [11] consider cooperative sensing by using a counting rule and derive optimal strategies under both the Neyman–Pearson criterion and the Bayesian criterion. The study in [12] presents a new cooperative wideband spectrum sensing scheme that exploits the spatial diversity among multiple SUs, which also contributes to the improvement of sensing accuracy. These studies have mainly focused on improving sensing accuracy, whereas sensing efficiency has been ignored. The enhancement of sensing efficiency has been investigated in [13] and [14]. The study in [13] introduces an opportunistic multichannel MAC protocol, which integrates two novel

cooperative sensing mechanisms, i.e., a random sensing policy and a negotiation-based sensing policy. The latter strategy assigns SUs to sense collaboratively different channels to improve the sensing efficiency. For the sake of reducing sensing overhead, the authors of [14] propose a multichannel cooperative sensing scheme, where the cooperative SUs are optimally selected to sense the distinct channels at the same time for sensing efficiency. These works assume that the sensing accuracy of one channel by a single SU is completely true, which may not be practical in real communication systems.

In addition, the given works did not consider the design of the cooperative MAC protocol for distributed networks and perform theoretical analysis of sensing overhead and throughput. Hence, we are interested in achieving both sensing accuracy and sensing efficiency by introducing a cooperation protocol in the MAC layer for CR networks. Several cognitive MAC protocols have been proposed in the literature to address various issues in the CR network [13], [17], [20]–[25]. However, these protocols do not leverage the benefit of cooperation at the MAC layer for enhancing the sensing efficiency without degrading the sensing accuracy.

In this paper, we propose a group-based cooperative MAC protocol called GC-MAC. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel. The sensing process will not stop unless an available spectrum channel is discovered. The purpose of team division is twofold: 1) sensing a channel by several SUs for the improvement of sensing accuracy; and 2) finding more spectrum opportunities by sensing distinct channels by different teams. Therefore, multiple distinct channels can be simultaneously detected within one sensing period, which leads to the enhancement of sensing efficiency.

To reduce the sensing overhead, we propose an SU-selecting algorithm for GC-MAC protocol. In the SU-selecting algorithm, we selectively choose the optimal number of the cooperative SUs for each team based on the channel occupation dynamics to substantially reduce sensing overhead. We analyze the sensing overhead and throughput in the saturation and no-saturation network cases, respectively. In the saturation networks, each SU always has data to transmit. In the nonsaturation networks, an SU may have an empty queue. In every network case, we consider two types of channel conditions: time-invariant channel and time-varying channel. In each condition, the sensing overhead and the throughput are incorporated into an achievable throughput maximization problem, which is formulated to find the key design parameters: the number of the cooperative teams and the number of SUs in one team. Furthermore, we present extensive examples to demonstrate the sensing efficiency compared with existing schemes and to show the determination of the crucial parameters. Simulation results demonstrate that our proposed scheme is able to achieve substantially higher throughput and lower sensing overhead, as compared to existing mechanisms.

The remainder of this paper is organized as follows. In Section II, the system models are introduced. Section III reports our proposed group-based MAC protocols for a cooperative CR network. Section IV introduces an SU-selecting algorithm for appropriately selecting the cooperative SUs to reduce the

sensing overhead. Then, we study the sensing overhead and achievable throughput in the saturation and nonsaturation networks in Sections V and VI, respectively. Section VII evaluates the performance of the proposed GC-MAC protocol based on our developed analytical models. Finally, we draw our conclusions in Section VIII.

II. SYSTEMS MODELS

A. Channel Usage Model

We assume that each licensed channel alternates between ON and OFF states, of which the OFF time is not used by PUs and hence can be exploited by the SUs. Assume that the duration of the ON and the OFF periods is independently exponentially distributed. For a given licensed channel, the duration of the ON period follows an exponentially distributed parameter μ_{ON} and the duration of OFF period with an exponentially distributed parameter μ_{OFF} . We define the channel availability as the normalized period that is available for SUs. Let p denote the channel availability. Then, we have $p = \mu_{\text{ON}} / (\mu_{\text{OFF}} + \mu_{\text{ON}})$. Similar to [13], in this paper, we mainly consider that the licensed channels used by the same set of PUs, i.e., the licensed channel availability information sensed by each SUs is consistent among all SUs.

We consider two scenarios depending on the channel dynamics. The first scenario is the time-invariant channel with unchanged channel data rate R . The throughput of the SU by using a time-invariant channel only depends on the constant data rate and the valid transmission time T_r . The second type of channel is the time-varying channel. The finite-state Markov channel (FSMC) model is employed to model the dynamics of the time-varying channel [19]. The dynamics of the time-varying channel is partitioned based on the channel data rate. It is reasonable to employ the channel data rate instead of the SNR, which has been used in conventional FSMC models. Since the channel data rate is closely relevant to the application layer requirements, hence, its usage facilitates the construction of resource demands from an application perspective. The set of the channel state is denoted as $\mathbf{M} \equiv \{1, 2, \dots, M\}$ with $|\mathbf{M}| = M$. Let c_i represent the channel state i ($i \in \mathbf{M}$). The state space is denoted as $\mathbf{S} \equiv \{c_i, i \in \mathbf{M}\}$. Let π_i ($i \in \mathbf{M}$) represent the steady-state probability at state c_i . Then, the steady-state probability can be solved using the similar technique in [19]. During data transmission within a frame, the time variation is slow enough that the channel data rate does not substantially change. This assumption is acceptable due to the short data transmission period within a frame and has been frequently used, e.g., in [18] and [26].

B. Energy Detection Model

To discuss our problem, we employ energy detection [7] as the spectrum sensing scheme. Both of the real-valued signal model and the complex-valued signal model are used to describe the received signal at the SU's receiver.

1) *Real-Valued Signal Model*: Let t_s be the sensing time and f_s be the sample frequency during sensing time. We denote N

as the number of samples in a sensing period, i.e., $N = t_s f_s$. The received signal $r_k(n)$ at the n th sample and the k th SU is given by

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ s_k(n) + w_k(n), & H_1 \end{cases}$$

where H_0 represents the hypothesis that PUs are absent, and H_1 represents the hypothesis that PUs are present. $s_k(n)$ represents the PU's transmitted signal, which is assumed as a real-valued Gaussian signal with zero mean and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with zero mean and variance σ_w^2 .

Let $e_k(r)$ denote the test statistic of the k th SU. Then, we have $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false-alarm probability of k th SU are given by

$$P_d^k = \Pr[e_k(r) > \lambda | H_1] \quad P_f^k = \Pr[e_k(r) > \lambda | H_0]$$

where λ is a decision threshold of the energy detector for a SU.

The test statistic $e(r)$ is known as a chi-square distribution with $(e(r)/\sigma_w^2) \sim \chi_N^2$ under hypothesis H_0 , and $(e(r)/\sigma_s^2 + \sigma_w^2) \sim \chi_N^2$ under hypothesis H_1 . However, if the number of samples is large, we can use the central limit theorem to approximate the chi-square distribution by Gaussian distribution [7] under hypothesis $H_z (z = 0, 1)$ with mean μ_z and variance σ_z^2 as

$$\begin{cases} \mu_0 = N\sigma_w^2 & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(\sigma_s^2 + \sigma_w^2) & \sigma_1^2 = 2N(\sigma_s^2 + \sigma_w^2)^2, & H_1. \end{cases}$$

Therefore, the probabilities P_d^k and P_f^k that can be approximated in terms of the Q function are given as follows:

$$P_d^k = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{2N}(\sigma_s^2 + \sigma_w^2)}\right) \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N}\sigma_w^2}\right)$$

where $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-(t^2/2)} dt$.

2) *Complex-Valued Signal Model*: Considering the complex-valued signal model, the received signal $r_k(n)$ at the n th sample and the k th SU can be given by

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ h_k s_k(n) + w_k(n), & H_1 \end{cases}$$

where the channel coefficients h_k are zero-mean unit-variance complex Gaussian random variables. $s_k(n)$ represents the PU's transmitted signal, which is assumed as a Gaussian signal with zero mean and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with zero mean and variance σ_w^2 .

The test statistic of the k th SU $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false-alarm probability of k th SU are given by

$$P_d^k = \Pr[e_k(r) > \lambda_c | H_1] \quad P_f^k = \Pr[e_k(r) > \lambda_c | H_0]$$

where λ_c is a decision threshold of the energy detector for a single SU considering the complex-valued signal model. For a large N , the distribution of $e_k(r)$ can be approximated as Gaussian distribution [7] with mean μ_z and variance σ_z^2 under hypothesis $H_z (z = 0, 1)$ as

$$\begin{cases} \mu_0 = N\sigma_w^2 & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(|h_k|^2\sigma_s^2 + \sigma_w^2) & \sigma_1^2 = 2N(|h_k|^2\sigma_s^2 + \sigma_w^2)^2, & H_1. \end{cases}$$

Finally, we can obtain the probabilities P_d^k and P_f^k in terms of the Q function as

$$P_d^k = Q\left(\frac{\lambda - N(|h_k|^2\sigma_s^2 + \sigma_w^2)}{\sqrt{2N}(|h_k|^2\sigma_s^2 + \sigma_w^2)}\right) \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N}\sigma_w^2}\right)$$

where $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-(t^2/2)} dt$.

C. Counting Rule

To improve sensing performance, an efficient fusion rule is needed to make a final decision to the availability of the channel. Depending on every SUs' individual decision from one team, there are three popular fusion rules: AND rule, OR rule, and majority rule [18]. The AND rule mainly focuses on maximizing the discovery of spectrum opportunities, which are deemed to exist if only one decision states that there is no PU. In the OR rule, as far as limiting the interference to the PU, the spectrum is assumed to be available only when all the reporting decisions declare that no PU is present. The last majority rule is based on the majority of the individual decisions. If more than half of the decisions declare the appearance of PU, then the final decision claims that there is a PU. Without loss of generality, we use the majority rule in this paper with the assumption that all the individual decisions are independent and that $P_d^k = P_d$ and $P_f^k = P_f$ [18]. Then, the joint detection probability and false-alarm probability by a j number of SUs are given by

$$P_d(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_d)^{j-\lceil \frac{j}{2} \rceil - y} P_d^{\lceil \frac{j}{2} \rceil + y} \quad (1)$$

$$P_f(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_f)^{j-\lceil \frac{j}{2} \rceil - y} P_f^{\lceil \frac{j}{2} \rceil + y} \quad (2)$$

III. GROUP-BASED COOPERATIVE MEDIUM ACCESS CONTROL

Here, we present the specifications of the proposed MAC protocol, together with the group-based cooperative spectrum sensing scheme and the SU-selecting algorithm. To describe our protocol conveniently, we have the following assumptions.

- Each SU is equipped with a single antenna that cannot operate the sensing and transmission at the same time. According to this constraint, the sensing overhead caused by sensing is unavoidable and cannot be neglected in protocol design.
- A common control channel is available for all SUs to communicate at any time.
- An SUs can be assigned to perform cooperative sensing even when they have the packets to transmit.

A time frame of the secondary network operation is divided into three phases: 1) reservation; 2) sensing; and 3) transmission. All SUs are categorized into three types as follows:

- Source SU (SU_s): an SU that has data to transmit;
- Cooperative SUs (SU_c): SUs that are selected for cooperative sensing;

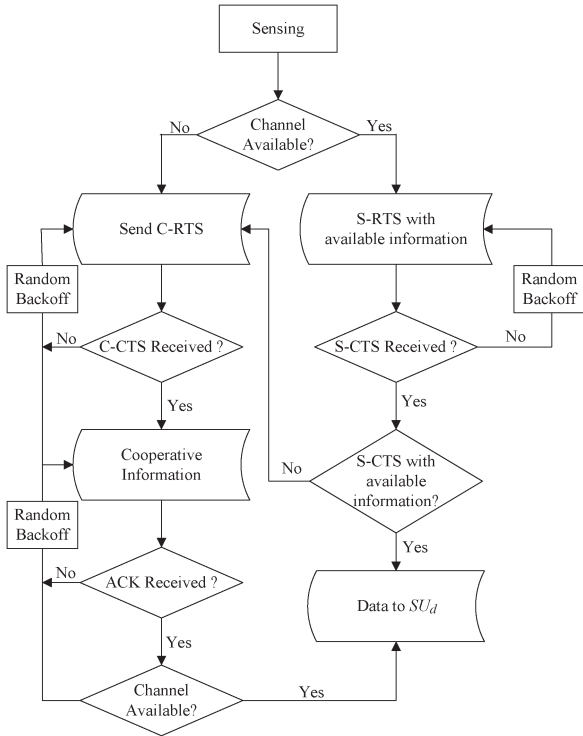


Fig. 1. Sensing work flow of SU_s .

- Destination SU (SU_d): an SU that receives the data packet from the source SU.

A. Reservation

In GC-MAC, any SU_s entering the network first try to perform a handshake with SU_d on the control channel to reserve a data channel. This allows the SU_s and SU_d to switch to the chosen channel for data transmission. Here, we use reservation for request-to-send/request for clear-to-send (R-RTS/R-CTS) packets for SU_s and SU_d to compete the data channel with other SUs. The SU_s will listen to control channel for a time interval T . If no R-RTS/R-CTS is received or time T is expired, the SU_s participates in the reservation process. Otherwise, it will defer and wait for the notification from the transmission pair or a timeout. Whenever there is at least one packet buffered in the queue, SU_s sends the reservation requirement to SU_d . Upon receiving the requirement, SU_d will reply, and other SUs overhearing these message exchanging cease their own sensing and wait for the notification from this transmission pair or a timer expiration. When the sensing or cooperative sensing is finished, other neighboring SUs start a new round of competition for the control channel with a random backoff.

B. Sensing

After reserving the data channel, SU_s and SU_d start to sense the spectrum channel. In this phase, we use secondary RTS/CTS (S-RTS/S-CTS) packets for spectrum sensing and negotiation between SU_s and SU_d . To indicate the mechanism of our scheme, the certificate RTS/CTS (C-RTS/CTS) packets are included in the RTS/CTS model for SU_c to acknowledge its participation. Fig. 1 shows the flowchart of the sensing

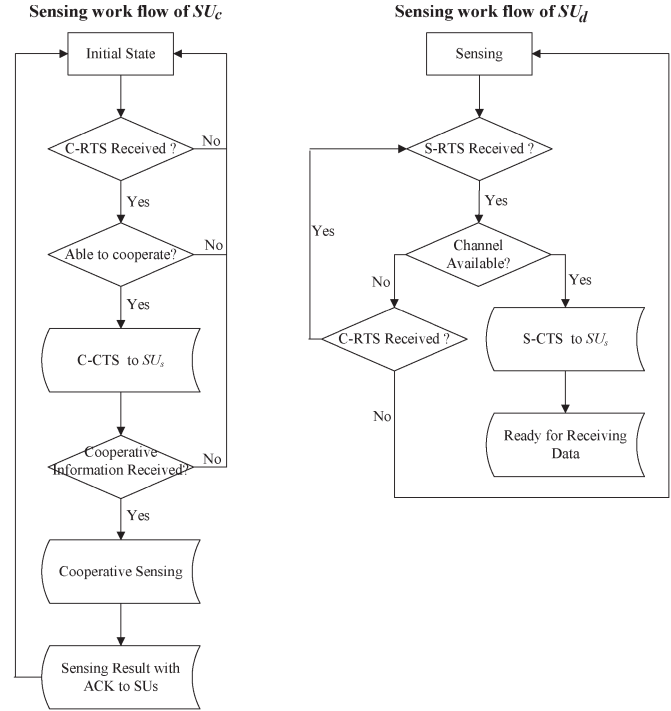


Fig. 2. Sensing work flow of SU_c and SU_d .

procedure of the source node SU_s . Fig. 2 shows the flowchart of the sensing procedures of SU_c and SU_d . In particular, we provide the detailed description as follows.

Source SU (SU_s):

- 1) SU_s senses the channel to judge the availability of the channel. If the channel is not occupied by a PU, SU_s sends an S-RTS packet to SU_d , including the availability information of the detected channel. Otherwise, SU_s sends the channel unavailability information to SU_d .
- 2) If an S-CTS packet from SU_d is not heard after a CTS timer, SU_s should perform a random backoff as if it encounters a collision. If SU_s receives the information of channel availability from SU_d , SU_s and SU_d will start the transmission phase (please refer to Section III-C). If SU_s receives the information of channel unavailability from SU_d , SU_s will send C-RTS to the neighborhood of SU_c and SU_d .
- 3) If SU_s does not receive any feedback from SU_c , it then sends cooperation requirement again after a random backoff. If the feedback is successfully received, SU_s counts the number of SU_c according to the SU-selecting algorithm (please refer to Section IV). When the number of SU_c 's satisfies the requirement of the cooperative sensing, SU_s stops sending the cooperation requirement to the neighborhood of SU_c and divides the chosen SU_c 's into a number of teams.
- 4) SU_s sends the cooperative information to the SU_c 's and then join the cooperative sensing with SU_c 's. Such information includes grouping information and the specific channels.
- 5) Upon receiving the sensing results, SU_s should declare the success of spectrum sensing and return to step 1.

Otherwise, SU_s should perform a random backoff and then return to step 4.

Cooperative SU (SU_c):

- 1) Upon receiving the cooperation requirement, SU_c sends feedback to the source node SU_s and waits for the cooperative information.
- 2) If the information for the cooperation is not received after a CTS timer, SU_c assumes that the information is lost and then reverts to the original state. Otherwise, SU_c starts the channel sensing based on the cooperative information.
- 3) After the time duration t_s , SU_c determines the PU's activity on the detected channel and sends cooperation acknowledgement to SU_s with the sensing result.

Destination SU (SU_d):

- 1) SU_d senses the same channel with SU_s in a synchronous way. After the sensing time t_s , SU_d makes the final decision about the state (ON/OFF) of the channel and waits for the sensing requirement from the source node SU_s .
- 2) If the destination node SU_d receives the sensing requirement with the sensing result from the source node SU_s , it delivers the sensing result back to SU_s . If the sensing result indicates that the channel is available, SU_d is ready for receiving data. Otherwise, SU_d waits for the cooperation requirement.
- 3) If cooperation requirement is received, SU_d will join the cooperative sensing and report the sensing results to SU_s . Then, SU_d returns to step 2. If neither a sensing requirement nor an cooperation requirement is heard after a timer, SU_d will go back to the initial state.

C. Transmission

After the source node SU_s and the destination node SU_d successfully find an available channel, they begin to use the channel to transmit data packets. Here, we use the transmit RTS/CTS (T-RTS/T-CTS) pair to indicate the transmission process. Before starting the transmission, SU_s will send T-RTS to SU_d for declaring the beginning of transmission. Upon receiving this requirement, SU_d replies T-CTS. If this feedback is received, SU_s sends the data packets to SU_d and sets acknowledgment timeout. When the acknowledgment from SU_d arrives, SU_s should declare the transmission success over the control channel. This success information ends the deferring of the neighboring SUs and starts a new round of reservation. If acknowledgment is not received after an acknowledgment timeout, SU_s should perform a random backoff and retransmit the data packets.

IV. REDUCING SENSING OVERHEAD VIA SECONDARY USER-SELECTING ALGORITHM

Here, we would like to reduce the sensing overhead by introducing an SU-selecting algorithm. In this algorithm, we employ the alternative pattern and the channel data rate of the SUs' used channel as the cooperative SU's selection conditions.

A. Channel Pattern for SUs

Each channel alternates between the ON state and the OFF state, which depends on the PUs' usage pattern. The channel that an SU uses may be busy after a period τ based on the previous idle status. During the busy period, the SUs are not allowed to access the channels, which are occupied by a PU. In this case, if these SUs are selected for cooperative sensing, the overhead of cooperation can be substantially reduced since sensing overhead is mainly incurred by ceasing transmissions during the cooperative sensing period. Let $I_\epsilon \in \{0, 1\}$ represent the binary channel state of channel ϵ . $I_\epsilon = 1$ refers to the ON state, and $I_\epsilon = 0$ refers to the OFF state. Let $P_{I_\epsilon 1}(\tau)$ denote the transition probability that the ϵ th channel will be busy after τ s with the initial state I_ϵ . We can express the transition probability $P_{01}(\tau)$ from the channel OFF state to the channel ON state as [27]

$$P_{01}(\tau) = p - pe^{-(\mu_{\text{OFF}} + \mu_{\text{ON}})\tau} \quad (3)$$

where p is the channel availability.

It is shown that the $P_{01}(\tau)$ only relate with the most recent channel state $I_\epsilon = 0$ and τ , which is the time between the most recent sensing and the current sensing. Considering that τ is different among the channels, then $P_{01}(\tau)$ is accordingly different with distinct SUs. To reduce the sensing overhead, our goal is to select the cooperative SUs with the high $P_{01}(\tau)$. In the following, we first present the optimal SU-selecting algorithm in the time-invariant channel case. Then, we derive the optimal selecting algorithm for the case where the channel has a time-varying feature.

B. SU-Selecting Algorithm

1) *Time-Invariant Channel Case:* A channel may stay at the idle state after τ s. The sensing overhead is expected to be high if the SUs who used these channels are chosen for cooperative sensing. Thereafter, to reduce sensing overhead, we select the cooperative SUs in the descending order of the probability $P_{01}(\tau)$. We can present the SU-selecting algorithm as follows.

- SU_s delivers the cooperative sensing request message (MSG-CSR) to the neighboring SU_c 's when a PU's activity is detected on a channel.
- The k th SU_c calculates $P_{01}(\tau_k)$, where τ_k represents the time duration from the moment of the most recent sensing to the moment of receiving MSG-CSR.
- SU_s selects the cooperative SU_c 's according to the descending order of $P_{01}(\tau_k)$.

The probability $P_{00}(\tau_k)$ can be alternatively employed since $P_{00}(\tau_k) = 1 - P_{01}(\tau_k)$. Hence, the SU-selecting algorithm can obtain the same strategy if we choose the cooperative SUs in the ascending order of the probability $P_{00}(\tau_k)$.

2) *Time-Varying Channel Case:* To reduce the sensing overhead, the SUs that have the highest $P_{01}(\tau)$ should be selected for cooperation in the time-invariant channel case. Here, the probability $P_{01}(\tau)$ represents the transition probability from the OFF state to the ON state. However, this strategy may not be efficient in the time-varying case where the channel data rate changes over the time. We choose the SUs not only based on

the probability $P_{01}(\tau)$ but also based on the channel data rate of their used channels. The SUs' used channels, which have both the lowest channel data rate and the highest $P_{01}(\tau)$ (or lowest $P_{00}(\tau)$), are selected to perform sensing and to search the available channels. As a consequence, in the time-varying channel case, the SU-selecting algorithm can be provided as follows.

- SU_s delivers the MSG-CSR to the SU_c s when PU's activity is detected on a channel.
- The k th SU_c calculates $P_{00}(\tau_k)$, where τ_k represents the time duration from the moment of the most recent sensing to the moment of receiving the message MSG-CSR.
- SU_s multiplies $P_{00}(\tau_k)$ by the channel data rate R_k of the k th SU's channel.
- SU_s selects the cooperative SUs according to the ascending order of $P_{00}(\tau_k)R_k$.

V. ANALYSIS AND OPTIMIZATION FOR THE SATURATION NETWORKS

Here, we will analyze the sensing overhead and throughput in a saturation networks. Our objective is to find two key design parameters: the number of cooperative teams and the number of SUs in one team. In a saturation network, we consider the CR network consisting of C licensed channels and a K number of SUs. The set of licensed channels is denoted as $\mathbf{C} \equiv \{1, 2, \dots, C\}$ with $|\mathbf{C}| = C$. The set of SUs is denoted as $\mathbf{K} \equiv \{1, 2, \dots, K\}$ with $|\mathbf{K}| = K$. We allow the cooperative sensing scheme to choose a certain number of SUs, which are further divided into U teams. Each team has a q ($q \geq 1$) number of SUs and is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U , and q satisfies $Uq \leq K$.

A. Time-Invariant Channel Case

1) *Sensing Overhead*: We define T_s as the total time duration spent by the k th cooperative SU after an n_s number of the cooperative sensing. With the proposed group-based sensing strategy, up to a U number of channels can be detected in one sensing period. Hence, all channels can be completely sensed within an $\lceil C/U \rceil$ number of sensing, and the variable n_s varies between 1 and $\lceil C/U \rceil$. If the channels can be found after an n_s number of cooperative sensing, the cooperative SUs cannot transmit any packets during $T_s = n_s t_s$ sensing periods. This operation is unfortunately unavoidable in the cooperative sensing. Let o_k^{TI} denote the sensing overhead caused by the k th cooperative SU in the time-invariant situation. Then, we have

$$o_k^{\text{TI}} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (4)$$

where R_k denotes the channel data rate of the channel used by the k th cooperative SU. Since the channel data rate is a constant in the time-invariant channel case, we obtain sensing overhead as

$$o_k^{\text{TI}} = \int_0^{T_s} R P_{00}(\tau_k) d\tau_k. \quad (5)$$

2) *Throughput*: Let P_s represent the probability that a channel is successfully found. This is equal to the probability that a channel is available and that no false alarm is generated by a q number of cooperative SUs. Then, we have $P_s = p[1 - P_f(q)]$, where p is the channel availability and $P_f(q)$ is given by (2). Let u denote the number of available channels that are found in cooperative sensing. The probability distribution function of the random variable u is given by $\binom{U}{u}(1 - P_s)^{U-u}P_s^u$. Then, we can obtain the probability $P_{\text{av},1}^{\text{TI}}$ that the available channels can be found in one cooperative sensing as

$$P_{\text{av},1}^{\text{TI}} = \sum_{u=1}^U \binom{U}{u} (1 - P_s)^{U-u} P_s^u. \quad (6)$$

With the proposed group-based sensing strategy, up to a U number of channels can be detected in one sensing period. Hence, all channels can be sensed completely within a $\lceil C/U \rceil$ number of sensing periods. We can then obtain the probability $P_{\text{av},n_s}^{\text{TI}}$ that an available channel is found after n_s cooperative sensing as follows:

$$P_{\text{av},n_s}^{\text{TI}} = (1 - P_{\text{av},1}^{\text{TI}})^{n_s-1} P_{\text{av},1}^{\text{TI}}. \quad (7)$$

Let T_r denote the average transmission time for an SU using a discovered available channel. We can derive the throughput of an SU by using this channel as follows:

$$\begin{aligned} \mathcal{T}^{\text{TI}} &= \sum_{n_s=1}^{\lceil C/U \rceil} P_{\text{av},n_s}^{\text{TI}} T_r R \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} T_r R \left[1 - \sum_{u=1}^U \binom{U}{u} (1 - P_s)^{U-u} P_s^u \right]^{n_s-1} \\ &\quad \times \left[\sum_{u=1}^U \binom{U}{u} (1 - P_s)^{U-u} P_s^u \right] \end{aligned} \quad (8)$$

where $T_r = \int_0^{\infty} \mu_{\text{OFF}} e^{-\mu_{\text{OFF}} t} dt = 1/\mu_{\text{OFF}}$.

To determine the optimal value of U and q , we introduce a new term, i.e., *the achievable throughput*, which is defined as the difference between sensing overhead and throughput. It is clear that the achievable throughput is able to demonstrate the purely achieved throughput after removing the penalty with respect to sensing overhead. For this perspective, the concept is able to capture the inherent tradeoff in the cooperative sensing.

Suppose that the available channel is discovered at the n_s th detection by a U number of teams. We can obtain the total sensing overhead \mathcal{O}^{TI} as follows:

$$\mathcal{O}^{\text{TI}} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s P_{\text{av},n_s}^{\text{TI}} q U o_k^{\text{TI}}. \quad (9)$$

Our objective is to find the optimal U and q for the group sensing to maximize the achievable throughput. The optimization problem is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{\text{TI}} = \mathcal{T}^{\text{TI}} - \mathcal{O}^{\text{TI}} \\ \text{s.t.} \quad & qU \leq K; \\ & P_d(q) \leq P_{d,\text{th}}; \quad P_d(q) \geq P_{d,\text{th}} \end{aligned} \quad (10)$$

where $P_{f,th}$ and $P_{d,th}$ represent the threshold of the false-alarm probability and detection probability, respectively. Based on the derived expression of \mathcal{T}^{TI} and \mathcal{O}^{TI} , the optimal number of cooperative teams and SUs in one team can be determined by solving (10). Considering the prohibitively high complexity of the optimization problem, we have resorted to numerical methods to find the optimal result to maximize the achievable throughput.

B. Time-Varying Channel Case

Here, we will perform an analytical analysis on sensing overhead and throughput in the time-varying channel case. It is worth noting that the analysis in the time-varying channel case is not a trivial extension of the analysis in the time-invariant channel case. On the one hand, the analysis in the time-invariant channel case is necessary to provide an easy understanding of the SU cooperation behavior and the inherent tradeoff between throughput and sensing overhead. On the other hand, the time-varying channel case is much more complicated than the time-invariant case by considering the complex channel dynamics. The development of sensing overhead and throughput is dependent on the channel dynamics, which leads to new equations for a channel data rate, sensing overhead, throughput, and hence, achievable throughput in the time-varying case.

1) *Sensing Overhead*: Based on the SU-selecting algorithm, we can analyze the sensing overhead caused by the group-based sensing under the time-varying channel case. Let $\bar{R} = [R_1, R_2, \dots, R_M]$ represent the channel-data-rate vector of length M . Without loss of generality, we suppose $R_1 < R_2 < \dots < R_M$. Let $\bar{X} = [X_1, \dots, X_K]$ be a random sample from \bar{R} of length K . Hereby, the vector \bar{X} represents the specific value of a parallel sensing and hence has length K instead of M . Let $X_k (k \in \mathbf{K})$ denote the k th-order statistics of the sample. Employing the order statistics theory [29], we can derive the probability $\Pr\{X_k = R_n\} (k \in \mathbf{K}; n \in \mathbf{M})$, which shows that the k th SU's channel data rate is equal to R_n . We suppose that there are an $(h-1)$ number of samples in \bar{X} with the probability $\Pr\{X_i < R_n\} (1 \leq i \leq h-1; 1 \leq h \leq k)$; an $(l-h+1)$ number of samples in \bar{X} with the probability $\Pr\{X_i = R_n\} (1 \leq i \leq l-h+1; k \leq l \leq K)$; and an $(n-l)$ number of samples in \bar{X} with the probability $\Pr\{X_i > R_n\} (1 \leq i \leq n-l)$.

The random variables X_i are statistically independent and identically distributed with the generic form X ; thus,

we have

$$\Pr\{X < R_n\} = \sum_{R_i < R_n} \Pr\{X = R_i\} = \sum_{i=1}^{n-1} \pi_i.$$

Since the $(h-1)$ samples could be any random samples from \bar{X} , we obtain the probability of this case $\binom{K}{h-1} (\sum_{i=1}^{n-1} \pi_i)^{h-1}$.

For the probability $\Pr\{X_i = R_n\}$, we have

$$\Pr\{X = R_n\} = \pi_n.$$

Since the number of $(l-h+1)$ samples could be any random samples from the rest of $(K-h+1)$ samples of X , we obtain the probability of this case as $\binom{K-h+1}{l-h+1} (\pi_n)^{l-h+1}$, i.e.,

$$\begin{aligned} \Pr\{X_i > R_n\} &= 1 - \Pr\{X \leq R_n\} \\ &= 1 - \sum_{R_i < R_n} \Pr\{X = R_i\} \\ &= 1 - \sum_{i=1}^n \pi_i. \end{aligned}$$

Similarly, we obtain the probability of this condition as $\binom{K-1}{K-} (1 - \sum_{i=1}^n \pi_i)^{K-l}$. By summarizing all possibilities, the probability $\Pr\{X_k = R_n\}$ is given by (11) at the bottom of the page. Then, the channel data rate of the selected SU, denoted as $R_k (k \in \mathbf{K})$, is given by

$$R_k = \sum_{n=1}^M \sum_{i=1}^n R_i \Pr\{X_k = R_n\}. \quad (12)$$

Let o_k^{TV} denote the sensing overhead caused by the cooperative SU $_k$ after an n_s number of cooperative sensing under the time-varying channel condition. We can obtain

$$o_k^{TV} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (13)$$

where $T_s = n_s t_s$ denotes the time spent by the k th cooperative SU after n_s number of sensing.

2) *Throughput*: Let v represent the number of spectrum channels that are found in a cooperative sensing. The probability density function of the random variable v is given by $\binom{U}{v} (1 - P_s)^{U-v} P_s^v$, where P_s is given by (1). Let P_{av}^{TV} denote the probability that an available channel can be found in one

$$\begin{aligned} \Pr\{X_k = R_n\} &= \sum_{l=k}^K \sum_{h=1}^k \left[\binom{K}{h-1} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} \binom{K-h+1}{l-h+1} (\pi_n)^{l-h+1} \binom{K-l}{K-l} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right] \\ &= \sum_{l=k}^K \sum_{h=1}^k \left[\frac{K!}{(h-1)!(l-h+1)!(K-1)!} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} (\pi_n)^{l-h+1} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right] \end{aligned} \quad (11)$$

cooperative sensing in the time-varying channel case. Then, we have

$$P_{av}^{\text{TV}} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v. \quad (14)$$

We need to find the available channel with the highest channel data rate by the U teams. We will select the channel that has the highest channel data rate in these v channels for the SU to access. Let R_m ($1 \leq m \leq M$) denote the highest channel rate in these v numbers of channels. It is worth noting that the subscript m in R_m represents the index of channel data rate, which ranges from 1 to M . Let $P_{\text{rate},v}$ denote the probability that there are channels whose maximum rate is no lower than R_m ($1 \leq m \leq M$) in the founded v channels. Then, we have

$$P_{\text{rate},v} = \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right]. \quad (15)$$

Conditioning on all possibilities on the random variable v , we obtain the probability P_{rate} that there are channels whose maximum rate is no lower than R_m ($1 \leq m \leq M$), i.e.,

$$P_{\text{rate}} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v P_{\text{rate},v}. \quad (16)$$

We obtain the probability P_{maxrate} that R_m is the maximal channel data rate from all discovered available channels, i.e.,

$$P_{\text{maxrate}} = (1 - P_{av}^{\text{TV}})^{n_s-1} P_{\text{rate}}. \quad (17)$$

With the proposed sensing strategy, each sensing period may find up to a U number of channels. Hence, all channels can be sensed completely within an $\lceil C/U \rceil$ number of sensing periods. We can derive the throughput of the SU by using this channel as

$$\begin{aligned} \mathcal{T}^{\text{TV}} &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{\text{maxrate}} T_r R_m \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M T_r R_m (1 - P_{av}^{\text{TV}})^{n_s-1} \sum_{v=1}^U \binom{U}{v} \\ &\quad \times (1 - P_s)^{U-v} P_s^v \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right] \end{aligned} \quad (18)$$

where $T_r = \int_0^\infty \mu_{\text{OFF}} e^{-\mu_{\text{OFF}} t} dt = 1/\mu_{\text{OFF}}$.

We formulate the achievable throughput optimization problem by considering both throughput and sensing overhead in the time-varying channel condition. The total sensing overhead \mathcal{O}^{TV} is given by

$$\mathcal{O}^{\text{TV}} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s q U P_{av}^{\text{TV}} o_k^{\text{TV}}. \quad (19)$$

Consequently, the achievable throughput maximization problem in the time-varying channel case is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{\text{TV}} = \mathcal{T}^{\text{TV}} - \mathcal{O}^{\text{TV}} \\ \text{s.t.} \quad & qU \leq K; \\ & P_f(q) \leq P_{f,\text{th}}; \quad P_d(q) \geq P_{d,\text{th}} \end{aligned} \quad (20)$$

where \mathcal{T}^{TV} and \mathcal{O}^{TV} are given by (18) and (19), respectively. By solving (20), we can find the optimal U and q for the group sensing to maximize the achievable throughput.

VI. ANALYSIS AND OPTIMIZATION FOR THE NONSATURATION NETWORKS

Here, we will derive the sensing overhead and throughput in the nonsaturation networks. Suppose that an SU may have an empty queue. In this network, we consider a discrete-time queue with an infinite capacity buffer for the queuing behavior of an SU. The packet arrival of the SUs is assumed to be a Poisson process with arrival rate λ_{pac} . The packets are served on a first-in-first-out (FIFO) basis. The service time of each packet is modeled as identically distributed nonnegative random variables, denoted as χ_n ($n \geq 1$), whose arrival process is independent to each another. The similar assumption has been frequently used in the literature, e.g., [13], [28]. Let $F(t)$ denote the service time cumulative distribution function (cdf) with mean $0 < 1/\mu = \int_0^\infty t dF(t)$. Let ρ represent the traffic load, and it is given by $\rho = \lambda_{\text{pac}}/\mu$. For a practical system, the traffic load is less than 1, i.e., $\rho < 1$.

Similar to the saturation network, we still consider the CR network consisting of C licensed channels and a K number of SUs. The cooperative SUs are divided into U teams. Each team has a q ($q \geq 1$) number of SUs. Each team is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U , and q also satisfies $Uq \leq K$. Next, we will formulate the throughput maximization problem with a time-invariant and time-varying channel, respectively.

A. Time-Invariant Channel Case

Since the channel data rate will not change with the time in the time-invariant channel case, the packet service time is a constant, which means we are able to employ the single-server queuing model $M/D/1$ to evaluate the group sensing scheme with the time-invariant channel.

Based on the result of [29], the variance of service time $E(\chi^2) = 0$ in the $M/D/1$ model. Let \bar{N}_q^{TI} denote the average number of packets in a queue for time-invariant channel case. Then, we have

$$\bar{N}_q^{\text{TI}} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\rho^2}{2(1-\rho)}. \quad (21)$$

1) *Sensing Overhead*: To reduce the sensing overhead, we still select qU SUs that have the lowest channel data rate and least $P_{00}(t)$ among K SUs in the nonsaturation network. As explained, each group sensing can sense a U number of channels.

Hence, all channels can be sensed completely within a $\lceil C/U \rceil$ number of group sensing. Let $N_{\text{sense}}^{\text{TI},n_s}$ be the total number of packets that can be transmitted in the n_s number of group sensing by the qU sensing SUs if they are not participating the group-based cooperative sensing. $N_{\text{sense}}^{\text{TI},n_s}$ is given by

$$N_{\text{sense}}^{\text{TI},n_s} = \min \left\{ n_s q U \bar{N}_q^{\text{TI}}, (qUT_s R_{\text{use}})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (22)$$

where R_{use} denotes the channel data rate of the using channel, l denotes the length of a packet, $T_s = t_s n_s$, and \bar{N}_q^{TI} is given by (21).

Suppose that the available channel is discovered at the n_s th detection by an U number of teams in a nonsaturation network. Then, in a time-invariant channel case, we can obtain the total sensing overhead $\mathcal{O}_{\text{nonsat}}^{\text{TI}}$ as follows:

$$\mathcal{O}_{\text{nonsat}}^{\text{TI}} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{\text{av},n_s}^{\text{TI}} N_{\text{sense}}^{\text{TI},n_s} l \quad (23)$$

where $P_{\text{av},n_s}^{\text{TI}}$ is given by (7).

2) *Throughput*: Let T_r denote the average transmission time for an SU using a discovered available channel. In the time-invariant channel case, the average number of packets that SUs send during T_r at the equilibrium state is given by

$$N_D^{\text{TI}} = \min \left\{ \bar{N}_q^{\text{TI}}, (T_r R_{\text{use}})/l \right\} \quad (24)$$

where $T_r = \int_0^\infty \mu_{\text{OFF}} e^{-\mu_{\text{OFF}} t} dt = 1/\mu_{\text{OFF}}$.

With the proposed sensing strategy, each sensing period may find up to a U number of channels. Hence, all channels can be sensed completely within a $\lceil C/U \rceil$ number of sensing periods. Hence, we can derive the throughput of an SU by using the discovered available channel as follows:

$$\mathcal{T}_{\text{nonsat}}^{\text{TI}} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{\text{av},n_s}^{\text{TI}} N_D^{\text{TI}} l \quad (25)$$

where the item $P_{\text{av},n_s}^{\text{TI}}$ is given by (14).

In terms of the achievable throughput maximization, we formulate the following problem:

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{\text{nonsat}}^{\text{TI}} = \mathcal{T}_{\text{nonsat}}^{\text{TI}} - \mathcal{O}_{\text{nonsat}}^{\text{TI}} \\ \text{s.t.} \quad & qU \leq K; \\ & P_f(q) \leq P_{f,\text{th}}; \quad P_d(q) \geq P_{d,\text{th}}. \end{aligned} \quad (26)$$

B. Time-Varying Channel Case

Considering the time-varying channel case, the channel data rate may vary from time slot to time slot. This alternative indicates that an SU's capacity is a random variable. Following this reasoning, we can use the M/G/1 queuing model.

1) *Sensing Overhead*: Since the service time of each packets depends on the channel data rate, we can express the cdf $F(t)$ as

$$F(t) = l/R_i(t) \quad (27)$$

where $R_i(t)$ denotes the channel data rate of the i th channel state at the t th time slot. Let \bar{N}_q^{TV} denote the average number of packets in a queue for a time-varying channel case. Then, we have

$$\bar{N}_q^{\text{TV}} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\lambda^2 E(\chi^2) + \rho^2}{2(1-\rho)} \quad (28)$$

where $E(\chi^2) = \int_0^\infty t^2 dF(t)$.

In the time-varying channel case, let $N_{\text{sense}}^{\text{TV},n_s}$ be the total number of packets that cannot be transmitted by the qU cooperative SUs in an n_s number of group sensing. $N_{\text{sense}}^{\text{TV},n_s}$ is given by

$$N_{\text{sense}}^{\text{TV},n_s} = \min \left\{ n_s q U \bar{N}_q^{\text{TV}}, (qUT_s R_{\text{use}})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (29)$$

where $T_s = t_s n_s$, and \bar{N}_q^{TV} is given by (28).

Then, in a time-varying channel case, the total sensing overhead for discovering an available channel can be obtained as follows:

$$\mathcal{O}_{\text{nonsat}}^{\text{TV}} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{\text{av}}^{\text{TV}} N_{\text{sense}}^{\text{TV},n_s} l. \quad (30)$$

2) *Throughput*: We use T_r to denote the average transmission time for an SU using a discovered available channel in the time-varying channel case. Then, the average number of packets that SUs send during T_r is given by

$$N_D^{\text{TV}} = \min \left\{ \bar{N}_q^{\text{TV}}, (T_r R_{\text{use}})/l \right\} \quad (31)$$

where $T_r = \int_0^\infty \mu_{\text{OFF}} e^{-\mu_{\text{OFF}} t} dt = 1/\mu_{\text{OFF}}$.

The proposed sensing strategy may find up to a U number of channels during each sensing period. All channels can be completely sensed within a $\lceil C/U \rceil$ number of sensing periods. Supposing that the available channel can be found after an n_s number of group sensing, we can obtain the throughput of an SU by using a discovered available channel in the time-varying channel case, i.e.,

$$\mathcal{T}_{\text{nonsat}}^{\text{TV}} = \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{\text{maxrate}} N_D^{\text{TV}} l \quad (32)$$

where the item P_{maxrate} is given by (17).

Finally, we formulate the following problem in terms of achievable throughput maximization:

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{\text{nonsat}}^{\text{TV}} = \mathcal{T}_{\text{nonsat}}^{\text{TV}} - \mathcal{O}_{\text{nonsat}}^{\text{TV}} \\ \text{s.t.} \quad & qU \leq K; \\ & P_f(q) \leq P_{f,\text{th}}; \quad P_d(q) \geq P_{d,\text{th}}. \end{aligned} \quad (33)$$

Considering the complexity of the optimization problems, we still use numerical methods to find the optimal result to maximize the achievable throughput in the nonsaturation network. The optimal results are provided in the following under time-invariant and time-varying channel conditions, respectively.

TABLE I
ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATIONS OF U AND j IN THE TIME-INVARIANT CHANNEL CASE

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.9422	0.9365	0.9428	0.9359	0.9162	0.9208	0.9184	0.9126	0.9050	0.8746
$q=2$	0.9631	0.9822	0.9376	0.9061	0.8635	—	—	—	—	—
$q=3$	0.9616	0.9151	0.8797	—	—	—	—	—	—	—
$q=4$	0.9366	0.8708	—	—	—	—	—	—	—	—
$q=5$	0.9059	0.8454	—	—	—	—	—	—	—	—
$q=6$	0.8887	—	—	—	—	—	—	—	—	—
$q=7$	0.8712	—	—	—	—	—	—	—	—	—
$q=8$	0.8527	—	—	—	—	—	—	—	—	—
$q=9$	0.8347	—	—	—	—	—	—	—	—	—
$q=10$	0.8163	—	—	—	—	—	—	—	—	—

TABLE II
ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATIONS OF U AND j IN THE TIME-VARYING CHANNEL CASE

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.7839	0.7798	0.7764	0.7713	0.7645	0.7600	0.7544	0.7483	0.7421	0.7341
$q=2$	0.7907	0.8154	0.7282	0.7935	0.7245	—	—	—	—	—
$q=3$	0.7864	0.7730	0.7515	—	—	—	—	—	—	—
$q=4$	0.7804	0.7571	—	—	—	—	—	—	—	—
$q=5$	0.7731	0.7474	—	—	—	—	—	—	—	—
$q=6$	0.7681	—	—	—	—	—	—	—	—	—
$q=7$	0.7630	—	—	—	—	—	—	—	—	—
$q=8$	0.7681	—	—	—	—	—	—	—	—	—
$q=9$	0.7525	—	—	—	—	—	—	—	—	—
$q=10$	0.7472	—	—	—	—	—	—	—	—	—

VII. SIMULATION RESULTS

Here, we demonstrate the performance of the proposed GC-MAC in CR networks. The network consists of total $C = 10$ licensed channels. The channel parameter of the OFF period $\mu_{\text{OFF}} = 1/100$. We concentrate on the low SNR situation; the SNR threshold for a PU at the tagged SU is $\gamma = -10$ dB. The channel bandwidth is 1 MHz, and the target probability of detection $P_d = 0.9$, which is an important parameter used by 802.22 standard [30]. The length of RTS/CTS packets and sensing period are 40 B and 1 ms, respectively. Considering the time-varying channel case, the number of channel data rate state is $M = 10$. Accordingly, the channel data rate of each channel ranges between 0.1–1 MB/s, which decreases or increases its value by 10% once every 5 ms.

Table I shows the impacts of the number of cooperative teams and the number of SUs in one team on the achievable saturation throughput in the time-invariant channel situation. In these examples, the channel availability p is set as $1/2$. We can determine the optimal achievable throughput by choosing appropriate parameters. From Table I, we observe that the achievable throughput is maximized as 0.9822. In the time-varying channel case, Table II shows the achievable saturation throughput and that the maximal value is 0.8154. The saturation throughput in the time-varying case is lower than that in the time-invariant case. This is expected since the channel data rate may be reduced in the time-varying condition due to fading and signal variation. Similarly, we can obtain the maximal

nonsaturation throughput in the time-invariant channel case and the time-invariant channel case as 0.9107 and 0.8095, respectively.

A. Achievable Throughput

We compare our GC-MAC, which uses a group-based cooperative sensing scheme (GCSS) with an accuracy priority cooperative sensing scheme (ACSS) [11] and an efficiency priority cooperative sensing scheme (ECSS) [13]. In the ACSS, every cooperative SU monitors a single channel during each sensing period. The main focus of this scheme is to improve sensing accuracy of a PU's activity. In the SCSS, the cooperative SUs are assigned to sense different channels simultaneously for the sensing efficiency enhancement. This sensing operation assumes that the sensing of each channel by a single SU is accurate, which however may be difficult to achieve in practical CR networks.

1) *Time-Invariant Channel Case*: Fig. 3 shows the throughput comparison among GCSS, ACSS, and ECSS in the time-invariant channel case when $p = 2/3$ and $1/2$. In this example, the sensing accuracy requirement is set as $P_{f, \text{th}} = 0.05$. It is observed that the achievable throughput in all three schemes increases with higher channel availability p , which is intuitively understandable. The result indicates that the GCSS is able to achieve a much higher throughput than ACSS and ECSS. This is because GCSS is able to search and find more

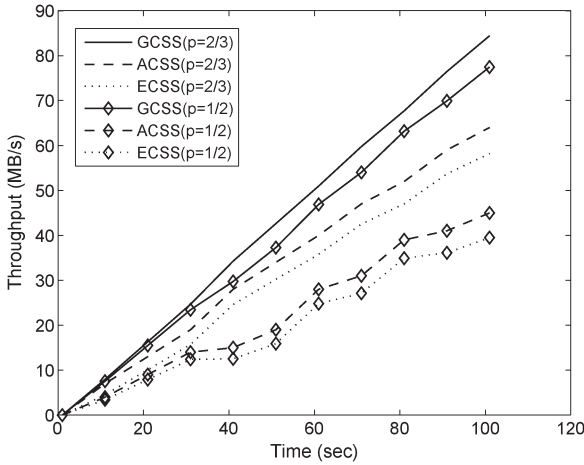


Fig. 3. Saturation throughput in the time-invariant channel case with different p .

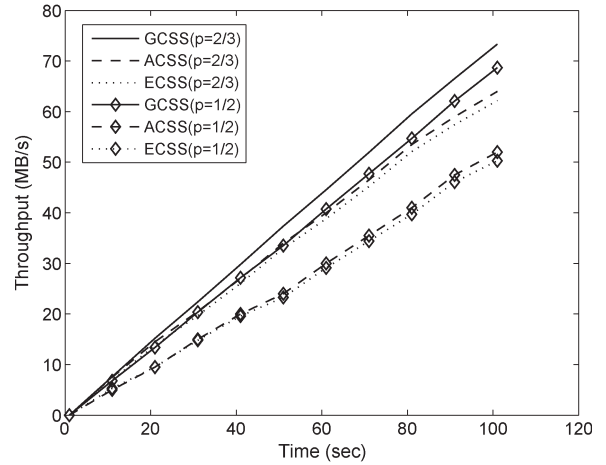


Fig. 5. Saturation throughput in the time-varying channel case with different p .

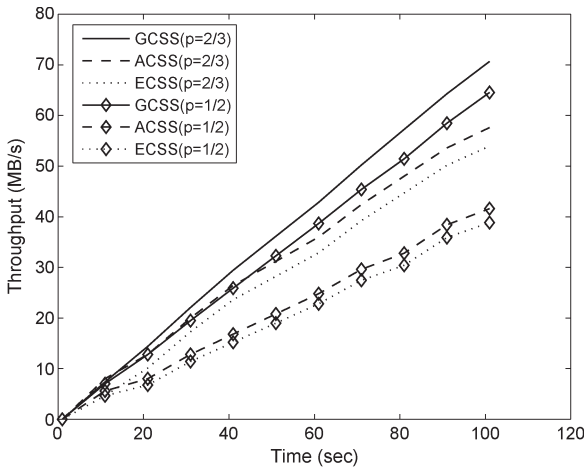


Fig. 4. Nonsaturation throughput in the time-invariant channel case with different p .

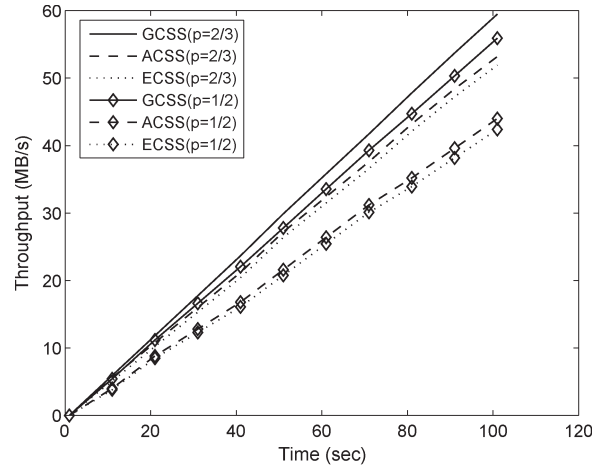


Fig. 6. Nonsaturation throughput in the time-varying channel case with different p .

spectrum opportunities. When the number of the cooperative SUs becomes larger, there is a higher chance to find the available channels, which leads to less sensing overhead. In addition, the ECSS uses all SUs to sense different channels, which causes less sensing accuracy of a single channel and leads to lower throughput. Comparatively, the proposed GCSS chooses the optimal number of teams and the number of SUs in each team. In this case, sensing overhead is significantly reduced, and throughput increases. As a consequence, our proposed GCSS is able to achieve high sensing efficiency with low sensing overhead.

Fig. 4 shows the nonsaturation throughput comparison among GCSS, ACSS, and ECSS in the time-invariant channel case when $p = 2/3, 1/2$. Again, the $P_{f,th} = 0.05$ is assumed as 0.05. It can be observed that the GCSS substantially outperforms the other two schemes. In addition, we notice that it will obtain higher throughput if the channel availability p becomes larger.

2) *Time-Varying Channel Case*: Figs. 5 and 6 show the saturation and nonsaturation throughput comparison among GCSS, ACSS, and ECSS in the time-varying channel case when $p = 2/3, 1/2$ and $P_{f,th} = 0.05$. The comparison indicates that GCSS is able to achieve higher throughput than ACSS and ECSS.

This is because GCSS is able to detect and find more spectrum opportunities even when the channel is dynamic. When the number of cooperative SUs becomes larger, our scheme not only finds the available channel quicker but also chooses the channel with a maximal rate if more than one available channels are found. Moreover, with the comparison to ECSS, GCSS has the advantage of reducing sensing overhead. As a consequence, the proposed GCSS achieves higher throughput in the time-varying channel case.

In addition, we illustrate the achievable throughput comparison among GCSS, ACSS, and ECSS under the complex-valued signal model. Figs. 7 and 8 show the saturation and nonsaturation throughput comparison among GCSS, ACSS, and ECSS in the time-varying channel case, respectively. We observe that GCSS can also obtain higher throughput than that in ACSS and ECSS. This observation indicates the effectiveness of our proposed MAC protocol in both of the real-valued and complex-valued signal models.

B. Sensing Overhead

1) *Time-Invariant Channel Case*: Fig. 9 shows sensing overhead among GCSS, ACSS, and ECSS in the time-invariant

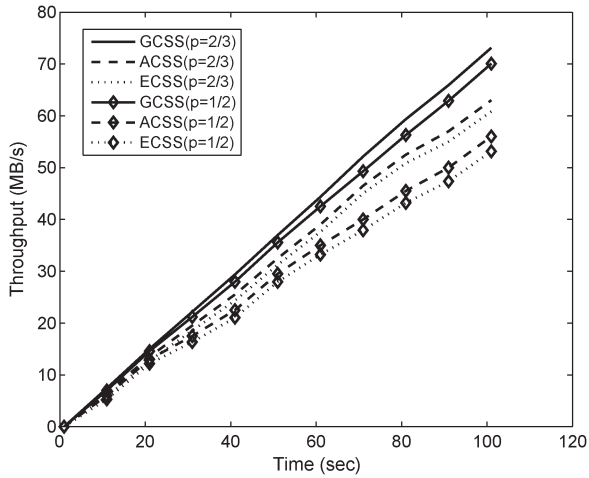


Fig. 7. Saturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

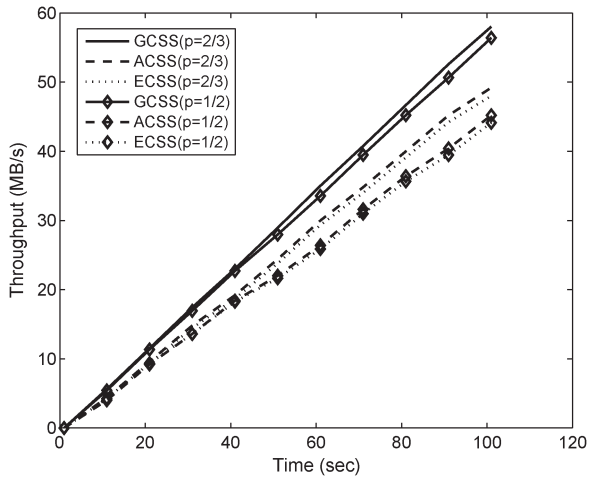


Fig. 8. Nonsaturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

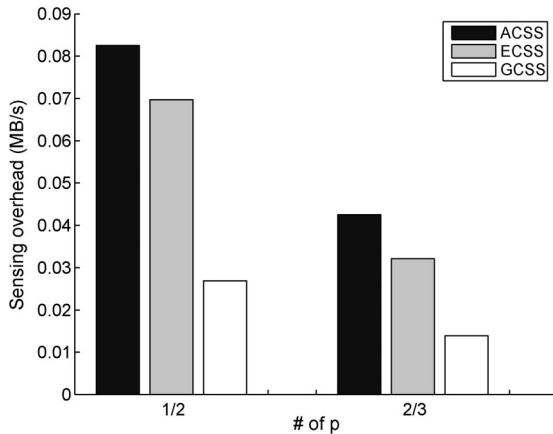


Fig. 9. Sensing overhead in the time-invariant channel case with different p for the saturation situation.

channel case for saturation situation. It is observed that GCSS generates the lowest sensing overhead. This can be explained as follows. the GCSS selects the SUs to cooperate by using the SU-selecting algorithm. The algorithm chooses the SUs

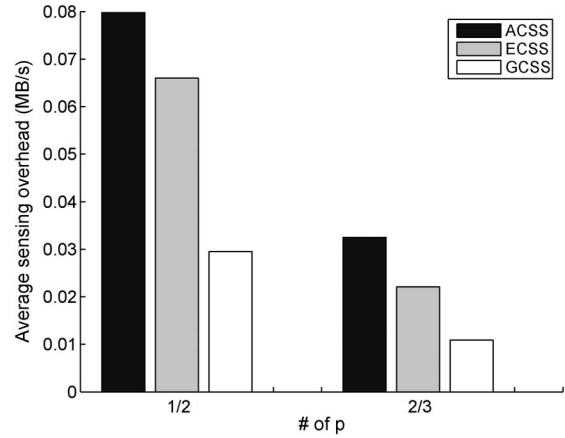


Fig. 10. Sensing overhead in the time-invariant channel case with different p for the nonsaturation situation.

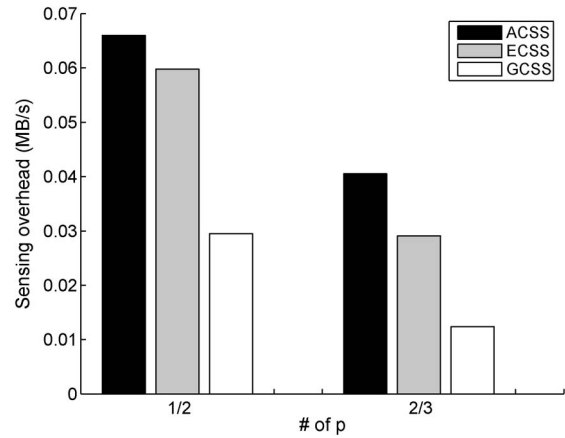


Fig. 11. Sensing overhead in the time-varying channel case with different p for the saturation situation.

with a low channel available probability P_{00} for the cooperative sensing. This operation can substantially reduce sensing overhead by avoiding the temporary stopping of the ongoing transmissions when their channels are occupied by PUs. Comparatively, ACSS and ECSS have no similar mechanisms and hence generate higher sensing overhead. Fig. 10 shows the sensing overhead for a nonsaturation situation. Similar observations and conclusions can be made. In addition, we notice that sensing overhead decreases when the channel availability p becomes larger. With more channel availability, there are more chances to find spectrum opportunities in a fixed period and, hence, less sensing overheads.

2) *Time-Varying Channel Case*: Considering the time-varying channel case, Figs. 11 and 12 show the sensing overhead with different channel availability p under saturation and nonsaturation situations, respectively. It is clear that sensing overhead becomes lower when the channel availability p increases. Again, the proposed GCSS incurs lower sensing overhead than ACSS and ECSS. With the time-varying channel, we have considered the channel dynamics and rate variation in selecting appropriate SUs to perform sensing. Following this way, sensing overhead in traditional cooperative sensing can be partially avoided.

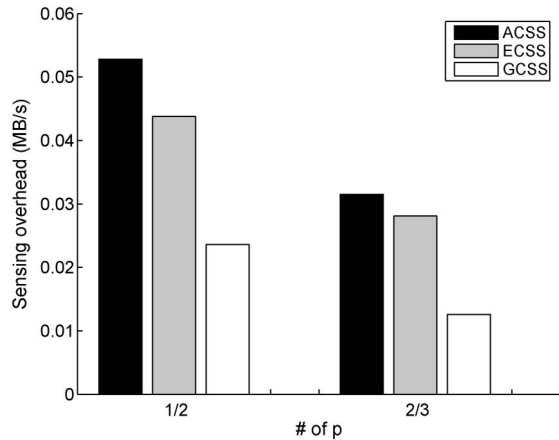


Fig. 12. Sensing overhead in the time-varying channel case with different p for the nonsaturation situation.

VIII. CONCLUSION

We have designed an efficient MAC protocol with selective grouping and cooperative sensing in CR networks. In our protocol, the cooperative MAC can quickly discover the spectrum opportunities without degrading sensing accuracy. An SU-selecting algorithm is proposed for specifically choosing the cooperative SUs to substantially reduce sensing overhead in both time-invariant and time-varying channel cases. We formulate the throughput maximization problems to determine the crucial design parameters and to investigate the tradeoff between sensing overhead and throughput. Simulation results show that our proposed protocol can significantly reduce sensing overhead without degrading sensing accuracy.

REFERENCES

- [1] "Second Memorandum Opinion and Order," Washington, DC, USA, ET Docket No. 10174, Sep. 2010.
- [2] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
- [3] R. Yu, Y. Zhang, S. Gjessing, Y. Chau, S. Xie, and M. Guizani, "Cognitive radio based hierarchical communications infrastructure for smart grid," *IEEE Netw.*, vol. 25, no. 5, pp. 6–14, Sep./Oct. 2011.
- [4] T. Wang, L. Song, and Z. Han, "Coalitional graph games for popular content distribution in cognitive radio VANETs," *IEEE Trans. Veh. Technol.*, to be published.
- [5] A. Jovicic and P. Viswanath, "Cognitive radio: An information-theoretic perspective," *IEEE Trans. Inf. Theory*, vol. 55, no. 9, pp. 3945–3958, Sep. 2009.
- [6] F. F. Digham, M. S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," *IEEE Trans. Commun.*, vol. 55, no. 1, pp. 21–24, Jan. 2007.
- [7] A. Ghasemi and E. S. Sousa, "Spectrum sensing in cognitive radio networks: Requirements, challenges and design trade-offs," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 32–39, Apr. 2008.
- [8] S. Atapattu, C. Tellambura, and H. Jiang, "Performance of an energy detector over channels with both multipath fading and shadowing," *IEEE Trans. Wireless Commun.*, vol. 9, no. 12, pp. 3662–3670, Dec. 2010.
- [9] S. Atapattu, C. Tellambura, and H. Jiang, "Energy detection based cooperative spectrum sensing in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1232–1241, Apr. 2011.
- [10] R.-F. Fan and H. Jiang, "Optimal multi-channel cooperative sensing in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 3, pp. 1128–1138, Mar. 2010.
- [11] J. Shen, S. Liu, L. Zeng, G. Xie, J. Gao, and Y. Liu, "Optimisation of cooperative spectrum sensing in cognitive radio network," *IET Commun.*, vol. 3, no. 7, pp. 1170–1178, Jul. 2009.
- [12] Z. Quan, S. Cui, and A. H. Sayed, "Optimal multiband joint detection for spectrum sensing in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 57, no. 3, pp. 1128–1140, Mar. 2009.
- [13] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 118–129, Jan. 2008.
- [14] Y. Liu, R. Yu, and S. Xie, "Optimal cooperative sensing scheme under time-varying channel for cognitive radio networks," in *Proc. IEEE Symp. New Front. DYSpan*, Nov. 2008, pp. 352–360.
- [15] R. Deng, J. Chen, C. Yuen, P. Cheng, and Y. Sun, "Energy-efficient cooperative spectrum sensing by optimal scheduling in sensor-aided cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 716–725, Feb. 2012.
- [16] S. Xie, Y. Liu, Y. Zhang, and R. Yu, "A parallel cooperative spectrum sensing in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 8, pp. 4079–4092, Oct. 2010.
- [17] H. A. Bany Salameh, M. M. Krunz, and O. Younis, "MAC protocol for opportunistic cognitive radio networks with soft guarantees," *IEEE Trans. Mobile Comput.*, vol. 8, no. 10, pp. 1339–1352, Oct. 2009.
- [18] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008.
- [19] H. S. Wang and N. Moayeri, "Finite-state Markov channel-A useful model for radio communication channels," *IEEE Trans. Veh. Technol.*, vol. 44, no. 1, pp. 163–171, Feb. 1995.
- [20] I. Krikidis, N. Devroye, and J. Thompson, "Stability analysis for cognitive radio with multi-access primary transmission," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 72–77, Jan. 2010.
- [21] Y.-X. Chen, Q. Zhao, and A. Swami, "Distributed spectrum sensing and access in cognitive radio networks with energy constraint," *IEEE Trans. Signal Process.*, vol. 57, no. 2, pp. 783–797, Feb. 2009.
- [22] S. R. Singh, B. De Silva, T. Luo, and M. Motani, "Dynamic spectrum cognitive MAC (DySCO-MAC) for wireless mesh & ad hoc networks," in *Proc. IEEE INFOCOM Conf. Comput. Commun. Workshops*, Mar. 2010, pp. 1–6.
- [23] J. Xiang, Y. Zhang, and T. Skeie, "Medium access control protocols in cognitive radio networks," *Wireless Commun. Mob. Comput.*, vol. 10, no. 1, pp. 31–49, Jan. 2010.
- [24] M. Timmers, S. Pollin, A. Dejonghe, L. Van der Perre, and F. Catthoor, "A distributed multichannel MAC protocol for multihop cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 446–459, Jan. 2010.
- [25] Q. Chen, M. Motani, W.-C. Wong, and A. Nallanathan, "Cooperative spectrum sensing strategies for cognitive radio mesh networks," *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 56–67, Feb. 2011.
- [26] W. S. Jeon and D. G. Jeong, "An advanced quiet-period management scheme for cognitive radio systems," *IEEE Trans. Veh. Technol.*, vol. 7, no. 2, pp. 1242–1256, Mar. 2010.
- [27] S. H. Song, K. Hamdi, and K. B. Letaief, "Spectrum sensing with active cognitive systems," *IEEE Trans. Wireless Commun.*, vol. 9, no. 6, pp. 1849–1854, Jun. 2010.
- [28] R. Urgaonkar and M. J. Neely, "Opportunistic scheduling with reliability guarantees in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 8, no. 6, pp. 766–777, Jun. 2009.
- [29] L. Kleinrock, *Queueing System*. New York, NY, USA: Wiley, 1975.
- [30] C. Cordeiro, K. Challapali, D. Birru, and S. Shankar, "IEEE802.22: The first worldwide wireless standard base on cognitive radios," in *Proc. IEEE Symp. New Front. Dyn. Spectr. Access Netw.*, Nov. 2005, pp. 328–337.



Yi Liu received the Ph.D. degree from South China University of Technology, Guangzhou, China, in 2011.

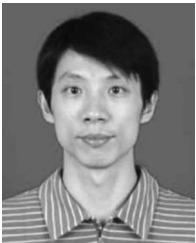
He was then with the Institute of Intelligent Information Processing, Guangdong University of Technology, Guangzhou. Since 2011, he has been with the Singapore University of Technology and Design, Singapore, where he is currently a Postdoctoral Researcher. His research interests include cognitive radio networks, cooperative communications, smart grids, and intelligent signal processing.



Shengli Xie (M'01–SM'02) received the M.S. degree in mathematics from Central China Normal University, Wuhan, China, in 1992 and the Ph.D. degree in control theory and applications from South China University of Technology, Guangzhou, China, in 1997.

He is currently a Full Professor and the Vice Head of the Institute of Automation and Radio Engineering with Guangdong University of Technology, Guangzhou. He is the author or co-author of two books and more than 70 scientific papers in journals and conference proceedings. His research interests include automatic control and blind signal processing.

Dr. Xie received the Second Prize in China's State Natural Science Award in 2009 for his work on blind source separation and identification.

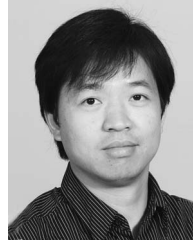


Rong Yu (S'05–M'08) received the Ph.D. degree from Tsinghua University, Beijing, China, in 2007.

He was then with the School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China. Since 2010, he has been with the Institute of Intelligent Information Processing, Guangdong University of Technology, Guangzhou, where he is currently an Associate Professor. He is the co-inventor of over ten patents and the author or co-author of over 50 international journal and conference papers. His research interests

include wireless communications and networking, cognitive radio, wireless sensor networks, and home networking.

Dr. Yu is currently serving as the Deputy Secretary General of the Internet of Things (IoT) Industry Alliance, Guangdong, China, and the Deputy Head of the IoT Engineering Center, Guangdong. He is a member of the Home Networking Standard Committee in China, where he leads the standardization work of three standards.



Yan Zhang (M'05–SM'10) received the Ph.D. degree from Nanyang Technological University, Singapore.

He is currently with the Simula Research Laboratory, Lysaker, Norway, and is an Adjunct Associate Professor with the University of Oslo, Oslo, Norway. His recent research interests include cognitive radio, smart grid, and machine-to-machine communications.

Dr. Zhang is an Associate Editor and a Guest Editor for a number of international journals. He serves as an Organizing Committee Chair for many international conferences.



Chau Yuen (SM'12) received the B.Eng. and Ph.D. degrees from Nanyang Technological University, Singapore, in 2000 and 2004, respectively.

In 2005, he was a Postdoctoral Fellow with Lucent Technologies Bell Labs, Murray Hill, NJ, USA. In 2008, he was a Visiting Assistant Professor with Hong Kong Polytechnic University, Kowloon, Hong Kong. From 2006 to 2010, he was with the Institute for Infocomm Research, Singapore, as a Senior Research Engineer. Since 2010, he has been an Assistant Professor with the Singapore University

of Technology and Design, Singapore.

Dr. Yuen serves as an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He received the IEEE Asia-Pacific Outstanding Young Researcher Award in 2012.