Cross-Layer Based Opportunistic MAC Protocols for QoS Provisionings Over Cognitive Radio Wireless Networks

Hang Su and Xi Zhang, *Senior Member, IEEE*

***Abstract*—We propose the cross-layer based opportunistic multi-channel medium access control (MAC) protocols, which integrate the spectrum sensing at physical (PHY) layer with the packet scheduling at MAC layer, for the wireless ad hoc networks. Specifically, the MAC protocols enable the secondary users to identify and utilize the leftover frequency spectrum in a way that constrains the level of interference to the primary users. In our proposed protocols, each secondary user is equipped with two transceivers. One transceiver is tuned to the dedicated control channel, while the other is designed specifically as a cognitive radio that can periodically sense and dynamically use the identified un-used channels. To obtain the channel state accurately, we propose two collaborative channel spectrum-sensing policies, namely, the random sensing policy and the negotiation-based sensing policy, to help the MAC protocols detect the availability of leftover channels. Under the random sensing policy, each secondary user just randomly selects one of the channels for sensing. On the other hand, under the negotiation-based sensing policy, different secondary users attempt to select the distinct channels to sense by overhearing the control packets over the control channel. We develop the Markov chain model and the $M/G^Y/1$-based queueing model to characterize the performance of our proposed multi-channel MAC protocols under the two types of channel-sensing policies for the saturation network and the non-saturation network scenarios, respectively. In the non-saturation network case, we quantitatively identify the tradeoff between the aggregate traffic throughput and the packet transmission delay, which can provide the insightful guidelines to improve the delay-QoS provisionings over cognitive radio wireless networks.**

***Index Terms*—Cognitive radio, multi-channel MAC, opportunistic spectrum access, cross-layer design, $M/G^Y/1$ queueing theory, QoS provisionings.**

I. Introduction

THE RAPID growth in the ubiquitous wireless services has imposed increasing stress on the fixed and limited radio spectrum. Allocating a fixed frequency band to each wireless service, which is the current frequency allocation policies, is an easy and natural approach to eliminate interference between different wireless services. However, extensive measurements reported indicate that the static frequency allocation results in a low utilization (only 6%) of the licensed radio spectrum in most of the time [1]. Even when a channel is actively used, the bursty nature of most data traffics still implies that a great deal of opportunities exist in using the spare spectrum.

In order to better utilize the licensed spectrum, the Federal Communication Committee (FCC) has recently suggested a new concept/policy for *dynamically* allocating the spectrum [2]. Consequently, a promising implementation technique of this concept, called the *cognitive radio*, is proposed to take advantage of this more open spectrum policy for alleviating the severe scarcity of spectrum bandwidth. Cognitive radio is typically built on the software-defined radio (SDR) technology, in which the transmitter's operating parameters, such as the frequency range, modulation type, and maximum transmission power can be dynamically adjusted by software [3]. In the cognitive radio networks, the *secondary* (unlicensed) users can periodically scan and identify the leftover[1] channels in the spectrum. Based on the scanned results, the secondary users dynamically tune their transceivers to the identified spare channel spectrum to communicate among themselves without interfering the communications of the *primary* (licensed) users.

Although the basic idea of cognitive radio is simple, the efficient design of cognitive radio networks imposes the new challenges that are not present in the conventional wireless networks [4]–[7]. Specifically, identifying the time-varying channel availability imposes a number of nontrivial design problems to the medium access control (MAC) layer. One of the most difficult, but important, design problems is how the secondary users decide when and which channel they should tune to in order to transmit/receive the secondary users' packets without affecting the communications among the primary users. This problem becomes even more challenging in wireless ad hoc networks where there are no centralized controllers, such as basestations or accessing points.

The research community has proposed several decentralized opportunistic MAC protocols [8]–[14]. In particular, the authors of [8], [9] developed a cognitive-radio MAC protocol based on the partially observable Markov decision processes (POMDPs) framework. Although this policy can well exploit the available frequency spectrum, its implementation is complicated and hardware-constrained because each secondary user needs to be equipped with multiple sensors to detect

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The authors are with the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843 USA (e-mails: hangsu@ece.tamu.edu; xizhang@ece.tamu.edu).

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[1]We use the words of *leftover* and *un-used* interchangeably in the rest of this paper.

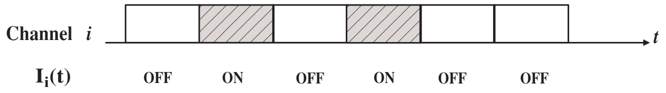

Fig. 1. The channel state for the i-th channel.

the channel activity in their scheme. The authors of [10] proposed the dynamic open spectrum sharing (DOSS) MAC protocol, which is also costly as it requires three separate sets of transceivers to operate on the control channel, data channel, and busy-tone channel, respectively. The authors of [11] proposed the cognitive MAC with statistical channel allocation, in which the secondary users select the channel that has the highest successful transmission probability to send packets based on the channel statistics. However, the computational complexity for determining the successful transmission probabilities increases quickly with the number of licensed channels. The author of [12] proposed a multi-channel opportunistic MAC protocol, which however targets only at the Global System for Mobile Communications (GSM) cellular networks. The authors of [13] developed a multi-channel cognitive MAC protocol, called C-MAC, which, however, does not differentiate the primary users and the secondary users. In [14], we developed a simple, but efficient, random sensing policy based opportunistic MAC protocol without taking into account the channel bonding/aggregation techniques. In addition, all these pervious works do not address the delay analyses, which play an important role in designing the QoS-provisionings over cognitive radio wireless networks.

To amend the aforementioned problems of the existing schemes, in this paper we propose the cross-layer based opportunistic multi-channel MAC protocols for wireless ad hoc networks. Our proposed schemes integrate the spectrum sensing policy at the physical (PHY) layer with packet scheduling at the MAC layer. Under our proposed schemes, each secondary user consists of a control transceiver working on the dedicated control channel and a SDR-based transceiver that can be dynamically tuned to any one of the licensed channels to sense for the spare spectrum, and then to receive/transmit the secondary users' packets. To detect the availability of the left-over channels, we propose the following two channel sensing policies, 1) the simple, but efficient, random sensing policy; 2) the performance-enhanced negotiation-based sensing policy. Our schemes smoothly coordinate the two transceivers of the secondary users, enabling them to collaboratively sense and dynamically utilize the available frequency spectrum. In addition, our proposed cognitive-radio MAC protocols do not need any centralized controllers.

We also rigorously analyze the throughput and the delay-QoS performances of our proposed schemes for the saturation network and the non-saturation network cases, respectively. First, in the saturation network case, where the secondary users always have *non-empty* queues, we develop the Markov chain model to analyze the saturation throughput for our proposed schemes. Second, based on the $M/G^Y/1$ queueing theory, we also develop an analytical model to investigate the more generalized non-saturation network case, in which the packet arrivals are characterized by a Poisson process. The average aggregate throughput and the average delay analyses derived

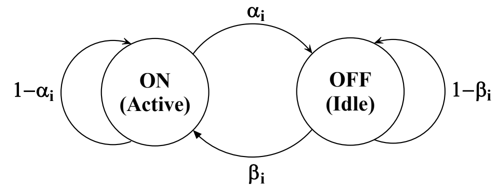

Fig. 2. The ON-OFF channel usage model for primary users.

for non-saturation network case can help devise the important parameters, such as the packet arrival rate, to support the QoS requirements for wireless networks.

The rest of this paper is organized as follows. Section II introduces the primary users' channel-usage model. Section III develops our proposed opportunistic multi-channel MAC protocols. Section IV develops the analytical model to analyze our proposed MAC protocols in the saturation network case. Applying the $M/G^Y/1$ queuing model, Section V analyzes the packet transmission delay and throughput of our proposed cognitive-radio MAC protocols in the non-saturation network case. Section VI evaluates our multi-channel MAC protocols based on our developed analytical models. The paper concludes with Section VII.

II. The Primary Users' Channel-Usage Model

As shown in Fig. 1, we consider a licensed spectrum band consisting of n channels. Each licensed channel is time-slotted such that the primary users communicate with each other in a synchronous manner. Meanwhile, a number of secondary users, which are synchronized with the primary users, opportunistically access the licensed spectrum without imposing interference to the primary users. In this paper, we mainly focus on the scenarios where all secondary users utilize the licensed channels used by the same set of primary users. This implies that the licensed channel availability information sensed by each secondary users is consistent among all secondary users. We model each channel as an ON-OFF source alternating between state ON (active) and state OFF (inactive). An ON/OFF channel usage model specifies a time slot in which the primary user signals is or isn't occupying a channel. The secondary users can utilize the OFF time slot to transmit their own packets. Suppose that each channel changes its state independently. Let α_i be the probability that the i-th channel transits from state ON to state OFF and β_i be the probability that the i-th channel transits from state OFF to state ON, where $1 \leq i \leq n$. Then, the channel state can be characterized by a two-state Markov chain as shown in Fig. 2.

For the i-th channel in time slot indexed by t with $t = 1, 2, \cdots, T, (T+1), (T+2), \cdots$, the state of the i-th channel, denoted by $I_i(t)$, corresponds to a binary random variable, with 0 and 1 representing the *idle* and the *active* states, respectively. Hence, sensing a given channel produces a binary random sequence. The network state in the t-th time slot can be characterized as $[I_1(t), I_2(t), \cdots, I_n(t)]$. Then, the i-th channel utilization, denoted by γ_i, with respect to the primary users, can be written as:

$$\gamma_i = \lim_{T\to\infty} \frac{\sum_{t=1}^{T} I_i(t)}{T} = \frac{\beta_i}{\alpha_i + \beta_i}, \qquad (1)$$

where $1 \leq i \leq n$.

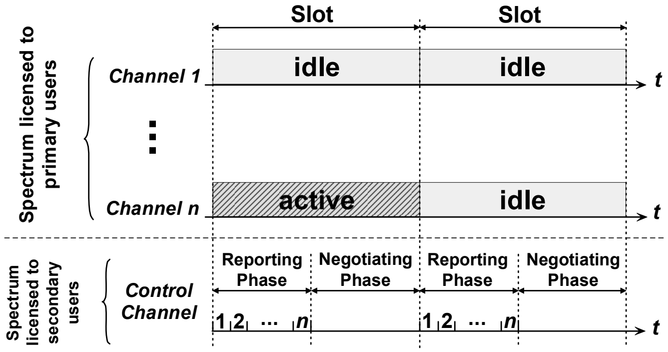

Fig. 3. The principle of our proposed MAC protocols.

Opportunistic MAC protocol: code for every secondary user

Initially: $NAC := 0, LAC := \emptyset, send\_flag := 0$

Reporting phase:

For Control transceiver:
- Listens on the control channel
- **Upon** receiving a beacon at k-th mini-slot
  - $NAC := NAC + 1$ //Update number of un-used chs.
  - $LAC(NAC) := k$ //Update list of un-used chs.
- **Upon** Informed by SDR that j-th channel is idle
  - Send a beacon at j-th mini-slot
  - $NAC := NAC + 1$ //Update number of un-used chs.
  - $LAC(NAC) := k$ //Update list of un-used chs.

For SDR transceiver:
- Senses channel j which is decided by the sensing policy.
- **If** channel j is idle
  - Inform Control transceiver that j-th channel is idle

Negotiating phase:

For Control transceiver:
- **Upon** receiving RTS
  - Update the channel it will sense according to sensing policy
  - send CTS to source node
- **Upon** receiving CTS
  - Update the channel it will sense according to sensing policy
  - **If** destination address is myself //negotiation is succeeded
    - Set $send\_flag := 1$ at the end of this phase
- **If** the outgoing queue is not empty
  - Contend to send RTS to the destination node

For SDR transceiver:
- **If** $send\_flag = 1$
  - $send\_flag := 0$
  - Transmit the data packets over all the channels in LAC

Fig. 4. Pseudo code of the MAC protocol for the secondary users, where NAC is the number of identified un-used channels, LAC is the list of identified un-used channels.

III. Our Proposed Multi-Channel MAC Protocols

A. Overview

In our proposed cognitive radio-based multi-channel MAC protocols, each secondary user is equipped with two transceivers. The first transceiver (called the control transceiver) is devoted to operating over the dedicated control channel. The secondary users use their control transceivers to obtain the information of the un-used licensed channels, and to negotiate with the other secondary users through the contention-based algorithms, such as IEEE 802.11 distributed coordination function (DCF) [15] and p-persistent Carrier Sense Multiple Access (CSMA) [16] protocols. The second transceiver consists of a SDR module such that it can tune to any one of the n licensed channels to sense for spare spectrum, receive/transmit the secondary users' packets. For convenience, we call the first transceiver the control transceiver and the second transceiver the SDR transceiver, respectively, in the rest of this paper. Our protocols do not need any centralized controllers, which is an attractive feature for all distributed wireless ad hoc networks.

Fig. 3 shows the principle of our proposed schemes. In the control channel, the time axis is divided into a number of periodical time slots. All the time slots of the control channel have the same length as those of licensed channels and the slots of both control channel and licensed channels are synchronized. In the control channel, each slot is divided into two phases, namely, the *reporting phase* and the *negotiating phase*. The reporting phase can be further divided into n mini-slots, each of them corresponding to one of the n licensed channels.

Fig. 4 describes the pseudo code for our proposed scheme. At the beginning of each time slot, secondary users sense the licensed channels, and then report the channel state by sending the beacons in the mini-slots. Since each secondary user is equipped with only one SDR transceiver, which can operate on one channel at a time, it cannot accurately know the states of all the channels by itself. The goal of the channel-state-report process is to enable the secondary users to have a large picture of all the channels' states through their cooperations. In particular, the secondary users use SDR transceivers to sense one of n licensed channels, say i-th channel, $(1 \le i \le n)$. If the secondary user perceives that the i-th channel is idle, then it uses the control transceiver to send a beacon during the i-th mini-slot over the control channel. Otherwise, it does not send any beacons. Each mini-slot lasts for T_{ms} time units, which is set to be long enough to determine whether channel is busy or not. Following the settings in IEEE 802.11a [15], we set T_{ms} to be equal to 9 μs in the rest of this paper. Clearly, if each of the n licensed channels is sensed by at least one secondary user, all the secondary users get the information about the activity of the entire licensed spectrum. We develop the channel sensing policies which aim at gaining as much channel information as possible in Section III-C. If we denote T_S, T_{RP}, and T_{NP} as the time duration of the time slot, the reporting phase, and the negotiating phase, respectively, then we obtain:

$$T_S = T_{RP} + T_{NP} = nT_{ms} + T_{NP}. \tag{2}$$

During the negotiating phase, the secondary users use the control transceivers to negotiate about the data channels among the secondary users by exchanging request-to-send (RTS) and clear-to-send (CTS) packets over the control channel. Meanwhile, the only secondary user which is the winner in contending for the data channels during the *last* time slot uses the SDR transceiver to transmit data packets over *all* the un-used licensed channels in the *current* time slot.

B. Channel Negotiation and Data Exchange

When a secondary user wants to initiate a transmission, it follows the p-persistent CSMA protocol to access the control channel to negotiate with the receiver. Particularly, the sender listens to the control channel and waits until it becomes idle. Then, it transmits the RTS packet with probability p. After the secondary user successfully receives CTS packet

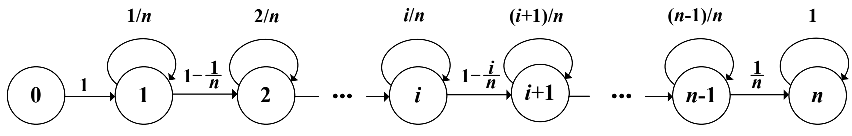

Fig. 5. The $(n+1)$-state Markov chain $\{S_u\}$ for the number of sensed channels, where the variable in each circle represents the number of distinct channels sensed by the secondary users.

since sending the last RTS, it gets the permission to transmit data packets in the coming next time slot. By using the channel bonding/aggregation techniques [17], this secondary user utilizes *all* leftover channels collectively to transmit the data packets.

Note that in our proposed scheme, the secondary users do not send the data packets over the licensed channels immediately after they successfully reserve the data channels at the same time slot. Instead, the secondary users transmit data packets in the next following time slot after they successfully exchange RTS/CTS packets with their destination secondary-users in the current time slot.

C. Channel Sensing Policies

To identify which channels are idle (i.e., not used by the primary users), the secondary users need a channel sensing policy to dynamically detect the states of channels. We develop two simple, but efficient, sensing mechanisms, namely, the *random sensing policy* (RSP) and the *negotiation-based sensing policy* (NSP) in this paper. Our following analyses show that our proposed schemes can efficiently utilize the unused frequency spectrum. We start with the simple random sensing policy, and then describe the enhanced negotiation-based sensing policy.

In the random sensing policy, the secondary users cooperate to sense the licensed channels. Each secondary user randomly chooses one of the n licensed channels for sensing. The chosen channels among all the secondary users are independent and identically distributed (i.i.d.). Let u, where $u = 1, 2, \cdots$, be the number of secondary users in the networks. Define a random variable, S_u, which stands for the total number of distinct channels that the secondary users have sensed given that there are u secondary users. Then, we develop a Markov chain model to calculate the probability mass function (pmf) of S_u, denoted by $\Pr\{S_u = s\}$, that the number of channels sensed by the secondary users is s with $s = 0, 1, \cdots, n$. Each secondary user *independently* and *uniformly* selects one of the n channels with probability of $1/n$. We can model the channel sensing process as a Markov chain, $\{S_u\}$, having $(n+1)$ states, as shown in Fig. 5, where the variable in the circle represents the number of channels sensed by the secondary users. The transition probability, denoted by $q_{i,j}$, of the Markov chain can be written as

$$q_{i,j} \triangleq \Pr\{S_{u+1} = j | S_u = i\} = \begin{cases} \frac{i}{n}, & j = i, \\ 1 - \frac{i}{n}, & j = i+1, \\ 0, & \text{otherwise}, \end{cases} \tag{3}$$

where $i, j = 0, 1, 2, \cdots, n$. Thus, we are able to derive the probability transition matrix for the Markov chain $\{S_u\}$, denoted by $\mathbf{Q}$, as follows:

$$\mathbf{Q} \triangleq \{q_{i,j}\} = \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & \frac{1}{n} & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{i}{n} & \frac{n-i}{n} & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & \frac{i+1}{n} & \frac{n-i-1}{n} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \frac{n-1}{n} & \frac{1}{n} \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix}_{(n+1)\times(n+1)} \tag{4}$$

where $q_{i,j}$ is defined by Eq. (3). Note that $\mathbf{Q}$ is an $(n+1) \times (n+1)$ upper bidiagonal matrix. The probability $\Pr\{S_u = s\}$ that the number of sensed channels is s on the condition that the number of secondary users is u is equivalent to the u-step transition probability from the state of 0 to the state of s for the Markov chain $\{S_u\}$, which can be expressed as

$$\Pr\{S_u = s\} = \mathbf{Q}^u|_{(0,s)}, \tag{5}$$

where $\mathbf{X}|_{(i,j)}$ denotes the element in position row i and column j of matrix $\mathbf{X}$. Clearly, the probability that all the licensed channels are sensed by the secondary users (i.e., $\Pr\{S_u = n\}$) only depends on the number of secondary users (i.e., u), and this probability gets larger when u increases. Using Eq. (5) to get the numerical results, we can further obtain the relationship between the number of secondary users and the number of sensed channels. For example, in the case where the number of licensed channels is 10, the probability that all licensed channels are sensed is close to 0.95 when $u = 50$, but this probability reduces to only 0.036 when u is equal to the number of licensed channels. Based on these observations, we obtain the following Facts.

Fact 1: In the random sensing policy, the more the number of secondary users is, the more likely the number of sensed channels is large.

We further study the asymptotical case in terms of the number of secondary users. When the number of secondary users goes to infinity, Eq. (5) can be rewritten as:

$$\lim_{u\to\infty} \Pr\{S_u = s\} = \begin{cases} 1, & s = n \\ 0, & 0 \le s \le (n-1), \end{cases} \tag{6}$$

which leads to the following Fact.

Fact 2: When the number of secondary users is large enough, the secondary users can sense all of the licensed channels even using the simple random sensing policy.

However, the simple channel-sensing policy is not good enough when the number of secondary users is smaller than or close to the number of the licensed channels. To amend this weakness of the random sensing policy, we further propose the negotiation-based sensing policy. The basic idea of the negotiation-based sensing policy is to let the secondary users know which channels are already sensed by their neighboring secondary users, and then select the different channels to sense at the next time slot.

From the view point of the secondary users, there are three types of channels in any given t-th time slot, including 1) the set of channels, denoted by $B_0(t)$, that are idle and sensed by the secondary users, 2) the set of channels, denoted by $B_1(t)$, that are busy and sensed by the secondary users, and 3) the set of channels, denoted by $B_2(t)$, that are not sensed by the secondary users. Note that $B_0(t)$ is also the set of mini-slots during which the beacon are sent, while $(B_1(t) \cup B_2(t))$ is the set of mini-slots during which no beacons appear in t-th time slot. Let $|B_0(t)|$, $|B_1(t)|$, and $|B_2(t)|$ be the cardinalities of $B_0(t)$, $B_1(t)$, and $B_2(t)$, respectively.

At the very beginning, the negotiation-based sensing policy also requires the secondary users to randomly select a licensed channel to sense, and then report the channel state by sending beacons in the reporting phase. Under the negotiation-based sensing policy, each RTS/CTS packet has a byte of special field containing the sensed channel information. During the negotiating phase, the secondary users include the information of the channel they have sensed into the RTS/CTS packets. When the secondary users exchange the RTS/CTS packets, the neighboring secondary users overhear these ongoing RTS/CTS packets transmitted, and then know whether they have sensed the same channels. If there are neighboring secondary users that sense the same channels as the sender in t-th time slot, each of them will sense another different licensed channel in the $(t+1)$-th time slot, which is randomly picked up from the set of $(B_1(t) \cup B_2(t))$.

Intuitively, the negotiation-based sensing policy will eventually attain the desired state, where all the channels are sensed by the secondary users if the number of secondary users are larger than or equal to the number channels, or otherwise each channel is sensed by no more than one secondary user. We show that the desired state is attainable by the negotiation-based sensing policy in the following discussions, and we will also evaluate how long it takes to attain the desired state in Section V.

To prove that the desired state is attainable, we first present the following proposition.

Proposition 1: (Non-decreasing Property) For the negotiation-based sensing policy, the number of licensed channels which are sensed by the secondary users in the $(t+1)$-th time slot is always larger than or equal to that in the t-th time slot, for any given $t = 0, 1, 2, \cdots$.

Proof: The proof is detailed in Appendix A. ∎

Proposition 2: If the number of secondary users is larger than or equal to the number of licensed channels, all the licensed channels can be eventually sensed by using the negotiation-based sensing policy.

Proof: Since the number of licensed channels that are sensed is non-decreasing function in terms of time index as shown in Proposition 1, the number of sensed channels continues to increase with some probability before all the channels are sensed. Thus, Proposition 2 follows, which shows that the desired state is attainable. ∎

IV. Throughput Analyses for The Saturation Network Case

Without loss of generality, we adopt p-persistent CSMA as the data channel accessing scheme for the secondary users during the negotiating phase. In this section, we develop an analytical model to analyze the aggregate throughput of our proposed scheme based on the channel sensing policies and p-persistent CSMA scheme under the saturation network case.

A. The p-persistent CSMA Scheme for Negotiating Phase

Under the p-persistent CSMA protocol, if the channel is detected as busy, the secondary user with a non-empty queue waits until channel becomes idle, and then transmits the packet with probability p. We consider the *saturation networks*, where each secondary user *always* has non-empty queue. Thus, all the secondary users contend for sending the RTS packets during the negotiating phase by using p-persistent CSMA. If we denote T_{succ} and T_{coll} as the time spent by a successful transmission and the time spent by an unsuccessful transmission, respectively, then we have

$$\begin{cases} T_{\text{succ}} = RTS + SIFS + CTS + DIFS, \\ T_{\text{coll}} = RTS + DIFS, \end{cases} \tag{7}$$

where RTS is the time spent by sending a RTS packet, CTS is the time spent by sending a CTS packet, $SIFS$ is the time interval of short inter-frame space (SIFS), and $DIFS$ is the time interval of DCF inter-frame space (DIFS).

In the p-persistent CSMA, if we denote P_{idle}, P_{succ}, and P_{coll} as the probability that the channel is idle, the probability that a node successfully transmits an RTS packet, and the probability that the collision occurs, respectively, then we obtain

$$\begin{cases} P_{\text{idle}} = (1-p)^u, \\ P_{\text{succ}} = up(1-p)^{u-1}, \\ P_{\text{coll}} = 1 - (1-p)^u - up(1-p)^{u-1}, \end{cases} \tag{8}$$

where u is the number of secondary users. Further, we can calculate the average time, denoted by $T(p,u)$, used for a successful transmission as follows:

$$T(p,u) = \frac{T_{ms}P_{\text{idle}} + T_{\text{succ}}P_{\text{succ}} + T_{\text{coll}}P_{\text{coll}}}{P_{\text{succ}}}, \tag{9}$$

where T_{ms} is the length of a mini-slot. To ensure that the secondary users can successfully exchange the RTS/CTS packets, $T(p,u)$ should be shorter than or equal to the length of negotiating phase, that is,

$$T(p,u) \leq T_{NP}, \tag{10}$$

where T_{NP} is defined in Eq. (2).

B. The Aggregate Throughput for the Saturation Networks

We study the aggregate saturation network throughput of the secondary users, each of which has a non-empty queue and always contends for data channels. We derive the throughput based on the random sensing policy and the throughput for the negotiation-based sensing policy, respectively, as follows.

B.1. The Random Sensing Policy Scheme.

Let $M(t)$ be the random number of the un-used channels at the t-th time slot. Suppose that there are n licensed channels and all licensed channels have the same channel utilization, denoted by γ, with respect to the primary users, i.e.,

$$\gamma = \gamma_i = \gamma_j, \forall\ 1 \leq i, j \leq n \text{ and } i \neq j, \tag{11}$$

where γ_i is determined by Eq. (1). Since the states among the n licensed channels are independent and the probability that the channel is active is γ, $M(t)$ follows the binomial distribution, that is,

$$\Pr\{M(t) = m\} = \binom{n}{m}\gamma^{n-m}(1-\gamma)^m. \tag{12}$$

Suppose that the secondary users can always sense the channels correctly. Similar to the analyses described in Section III, we can use a Markov chain to derive the distribution of the number of un-used channels identified by the secondary users. Given $M(t) = m$ at t-th time slot, we can get the conditional transition probabilities, denoted by $w_{i,j}$ with $0 \leq i, j \leq m$, as follows:

$$\Pr\{w_{i,j}|M(t) = m\} = \begin{cases} 1 - \left(\frac{m-i}{n}\right), & i = j, \\ \left(\frac{m-i}{n}\right), & j = i+1, \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

where $0 \leq m \leq n$. Given $M(t) = m$, the above transition probabilities generate the probability transition matrix, denoted by $\mathbf{W}_m$, which is a $(m+1) \times (m+1)$ upper bidiagonal matrix. Let u be the number of secondary users. Given $M(t) = m$, we obtain the probability that the random number, denoted by $L_{RSP}(t)$, of un-used channels perceived by the secondary users is equal to i at t-th time slot, as follows:

$$\Pr\{L_{RSP}(t) = i|M(t) = m\} = (\mathbf{W}_m)^u|_{(0,i)}, \tag{14}$$

where $0 \leq i \leq m$, and $\mathbf{X}|_{(i,j)}$ represents the element in position row i and column j of matrix $\mathbf{X}$. Using Eqs. (14) and (12), we can obtain the pmf for the number of identified un-used channels as follows:

$$\begin{aligned} &\Pr\{L_{RSP}(t) = i\} \\ &= \textstyle\sum_{m=0}^{n} \Pr\{M(t) = m\} \Pr\{L_{RSP}(t) = i|M(t) = m\} \\ &= \begin{cases} \sum_{m=i}^{n} \binom{n}{m}\gamma^{n-m}(1-\gamma)^m[(\mathbf{W}_m)^u|_{(0,i)}], & 0 \leq i \leq n, \\ 0, & \text{otherwise} \end{cases} \end{aligned} \tag{15}$$

If we let $\overline{L}_{RSP}$ be the average number of leftover channels that the secondary users can utilize, then we obtain

$$\overline{L}_{RSP} = \sum_{i=0}^{n} i \Pr\{L_{RSP}(t) = i\}. \tag{16}$$

Let the data rate of i-th licensed channel for the secondary users be R_i, where $0 \leq i \leq n$. Without loss of generality, we assume that all the n licensed channels have the same bandwidth, i.e., $R_i = R_j = R, \forall\ 0 \leq i, j \leq n$ and $i \neq j$. Since the transmission over the data channels are contention-free in our proposed protocols, we obtain the aggregate throughput, denoted by θ_{RSP}, for the secondary users as follows:

$$\theta_{RSP} = \frac{\overline{L}_{RSP} R T_{NP}}{T_S}, \tag{17}$$

where the factor of T_{NP}/T_S is due to the fact that the data transmission starts immediately after the reporting phase and continues for a period of T_{NP} in every time slot.

B.2. The Negotiation-Based Sensing Policy Scheme.

We study the saturation network throughput achieved by the negotiation-based sensing policy after it attains the desired state. We obtain the probability that the random number, denoted by $L_{NSP}(t)$, of un-used channels perceived by the secondary users is equal to i at the t-th time slot as follows:

$$\begin{aligned} &\Pr\{L_{NSP}(t) = i\} \\ &= \begin{cases} \binom{n}{i}\gamma^{n-i}(1-\gamma)^i, & u \geq n \text{ and } 0 \leq i \leq n, \\ \binom{u}{i}\gamma^{u-i}(1-\gamma)^i, & u < n \text{ and } 0 \leq i \leq u, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{18}$$

If we let $\overline{L}_{NSP}$ be the average number of un-used channels that the secondary users can utilize for negotiation-based sensing policy, then we obtain

$$\overline{L}_{NSP} = \sum_{i=0}^{n} i \Pr\{L_{NSP}(t) = i\}. \tag{19}$$

Then, we get the aggregate throughput, denoted by θ_{NSP}, for the saturation networks under the negotiation-based sensing policy as follows:

$$\theta_{NSP} = \frac{\overline{L}_{NSP} R T_{NP}}{T_S}. \tag{20}$$

V. Throughput and Packet Transmission Delay Analyses for The Non-Saturation Network Case

In this section, we analyze the our proposed protocols' performance, including the aggregate throughput, queueing delay, and service delay for the non-saturation-network case, where the secondary users may have the empty queues. Without loss of generality while making the analysis trackable, we assume that the packets of the secondary users arrive according to the Poisson process with a mean arrival rate λ [16] [18] [19]. For convenience of presentation, we call the procedure, during which a secondary user successfully reserves the data channels and transmits data packets, a *service procedure*, or simply, a *service*, in the following discussions.

Thanks to the channel-bonding technology, the secondary users can send multiple data packets during every time slot which they have successfully reserved in the negotiating phases. Note that the number of data packets that a secondary user can send at a time slot depends on the number of identified un-used channels during that time slot, which is a random variable. This implies that the service capacity for the secondary users *varies* from time slot to time slot.

Therefore, for this non-saturation-network case, we use the single-server bulk-service queueing model, $M/G^Y/1$, to investigate the aggregate throughput, queueing delay, and service delay, where Y stands for the variable service capacity.

To derive the queueing delay and aggregate throughput, we need to obtain the equilibrium-state distribution of the number of buffered packets in the queue for any given secondary user at any random points. We start with studying the random number, $N_\tau^+, \tau = 0, 1, 2, \cdots$, where τ is used to index the services, of the packets in the system for a given secondary user immediately after the τ-th service. The probability, denoted by P_j^+, that the system has j packets in the equilibrium state can be expressed as:

$$P_j^+ = \lim_{\tau\to\infty} \Pr\{N_\tau^+ = j\}. \tag{21}$$

Let $Y_\tau, \tau = 0, 1, 2, \cdots$ be the service capacity during the τ-th service. That is, the given secondary user can send $\mathbf{min}\{Y_\tau, \text{entire queue length}\}$ packets during the τ-th service. The distribution of Y_τ depends on the number of identified un-used channels, and thus we obtain Y_τ's distributions for random sensing and negotiation-based sensing policies, respectively, as follows:

$$\Pr\{Y_\tau = i\} = \begin{cases} \Pr\{L_{RSP}(\tau) = i\}\lfloor\frac{T_{NP}R}{\ell}\rfloor, \text{ for RSP,} \\ \Pr\{L_{NSP}(\tau) = i\}\lfloor\frac{T_{NP}R}{\ell}\rfloor, \text{ for NSP.} \end{cases} \tag{22}$$

where ℓ is the length of the data packets, R is the data rate for each channel, T_{NP} is the length of the negotiating phase, and the distributions of L_{RSP} and L_{NSP} during the τ-th service are characterized by Eqs. (15) and (18), respectively. Then, the pmf, denoted by y_i, that the given secondary user sends i data packets during a service at the equilibrium state, can be determined by

$$y_i = \lim_{\tau\to\infty} \Pr\{Y_\tau = i\}. \tag{23}$$

Note that the sequence of $\{y_i\}$ is independent of the arrival process of the packets for a given secondary user. Then, we get the average number, denoted by $\overline{y}$, of packets that a secondary user can send during a service as follows:

$$\overline{y} = \begin{cases} \overline{L}_{RSP}\lfloor\frac{T_{NP}R}{\ell}\rfloor, & \text{for RSP,} \\ \overline{L}_{NSP}\lfloor\frac{T_{NP}R}{\ell}\rfloor, & \text{for NSP,} \end{cases} \tag{24}$$

where $\overline{L}_{RSP}$ and $\overline{L}_{NSP}$ are given by Eqs. (16) and (19), respectively. We define

$$\begin{cases} \phi_j \triangleq \sum_{m=j}^n y_m, \\ \Phi_j(z) \triangleq \sum_{m=j}^n y_m z^m, \end{cases} \tag{25}$$

where $j = 0, 1, 2, \cdots$ and n is the number of licensed channels. Note that $\Phi_0(z)$ is the probability generating function (PGF) for $\{y_i\}$ and $\Phi_0(1) = \phi_0$.

Let p_s be the probability that a given secondary user can successfully reserve the data channels and V be the number of time slots spent to successfully reserve the data channels (i.e., service period) respectively. Since the p-persistent CSMA scheme is fair to each secondary user, p_s is inversely proportional to the number of secondary users (u), i.e.,

$$p_s = \frac{1}{u}. \tag{26}$$

Then, the service period, denoted by V, follows the geometric distribution, which has the following pmf:

$$\Pr\{V = v\} = p_s(1-p_s)^{v-1} = \frac{(u-1)^{v-1}}{u^v}, \tag{27}$$

where $v = 1, 2, \cdots$. Thus, we can get the average service period, denoted by $E[V]$ for a given secondary user as follows:

$$E[V] = \frac{1}{p_s} = u. \tag{28}$$

Consequently, we can calculate the system utilization, denoted by ρ, as follows:

$$\rho \triangleq \frac{\lambda E[V]}{\overline{y}} = \frac{\lambda u}{\overline{y}}, \tag{29}$$

where $\overline{y}$ is given by Eq. (24). For the equilibrium-state probability distribution to exist, ρ should be less than 1.

Let ψ be the random number of arrived packets for a given secondary user during the τ-th service. Since the packet arrivals comply with the Poisson process, given that the service period has v time slots, we obtain the probability that the number of arrived packets is j as follows:

$$\Pr\{\psi = j | V = v\} = \frac{e^{-\lambda v}(\lambda v)^j}{j!}. \tag{30}$$

Removing the conditioning on V in Eq. (30), we get the probability that the number of arrived packets is j as follows:

$$\begin{aligned} \Pr\{\psi = j\} &= \sum_{v=1}^{\infty} \Pr\{\psi = j | V = v\} \Pr\{V = v\} \\ &= \sum_{v=1}^{\infty} \frac{e^{-\lambda v}(\lambda v)^j}{j!} \left[p_s(1-p_s)^{v-1}\right]. \end{aligned} \tag{31}$$

Then, we get the PGF, denoted by $\Psi(z)$, of $\Pr\{\psi = j\}$ as follows:

$$\begin{aligned} \Psi(z) &= \sum_{j=0}^{\infty} \Pr\{\psi = j\} z^j \\ &= \sum_{j=0}^{\infty}\sum_{v=1}^{\infty} \frac{e^{-\lambda v}(\lambda v)^j}{j!} \left[p_s(1-p_s)^{v-1}\right] z^j \\ &= \frac{e^{\lambda(z-1)}}{u-(u-1)e^{\lambda(z-1)}}. \end{aligned} \tag{32}$$

Based on [20], the PGF, denoted by $P^+(z)$, of P_j^+ can be derived as

$$P^+(z) = \frac{\sum_{i=0}^n P_i^+[z^n\phi_i - z^i\Phi_i(z^{-1})]}{z^n\left[\frac{1}{\Psi(z)} - \Phi_0(z^{-1})\right]}. \tag{33}$$

Setting the denominator of Eq. (33) to be zero, we have

$$\Psi(z)\Phi_0(z^{-1}) = 1. \tag{34}$$

Solving Eq. (34), we can obtain $(n-1)$ roots, denoted by $z_1, z_2, \cdots, z_{n-1}$, respectively, which are located inside the unit circle, and one root which is located on the unit circle [21]. Therefore, P_j^+ can be determined by Eq. (35), where a_j is the coefficient of z^j in $\left[(1-z)\prod_{i=1}^{n-1}(1-zz_i^{-1})\right]$, with $0 \le j \le n$.

The average number of packets, denoted by L^+, buffered in the system after a service at the equilibrium state is the first moment of N_τ^+, and thus can be obtained by Eq. (36), where $f^{(i)}(\cdot)$ indicates the i-th derivative of $f(\cdot)$.

After obtaining all the probability properties of the equilibrium-state number, N_τ^+, of packets buffered in the system, we proceed to study the properties for number of packets in the queue at any random point. Let N_q be the equilibrium-state number of packets in the queue at a random point in time for a given secondary user and let $P_j = \Pr\{N_q = j\}$ be the probability that the queue for any given secondary user has

$$P_j^+ = \begin{cases} (\overline{y}/y_n)(1-\rho)\prod_{i=1}^{n-1} z_i(z_i-1)^{-1}, & j=0, \\ P_0^+ a_j - \sum_{i=n-j}^{n-1} P_{j-n+i}^+ y_i/y_n, & 1 \le j < n, \\ \Big[P_0^+ \Pr\{\psi = j-n\} a_j y_j + P_{j-n}^+ - y_n \sum_{i=n}^{j-1} P_i^+ \Pr\{\psi = j-i\} & \\ \quad - \sum_{i=0}^{n-1}\sum_{k=0}^{j-n} P_{j+i-k-n}^+ y_i \Pr\{\psi = k\}\Big] / \left(y_n \Pr\{\psi = 0\}\right), & j \ge n, \end{cases} \tag{35}$$

$$L^+ = \frac{d}{dz}P^+(z)\bigg|_{z=1} = \frac{\lambda^2\Psi^{(2)}(1) + \Phi_0^{(2)}(1)}{2\overline{y}(1-\rho)} + \frac{1-n+\rho(n-\rho\overline{y})}{1-\rho} + \sum_{i=1}^{n-1}(1-z_i)^{-1}. \tag{36}$$

j packets at a random point in the equilibrium state. Then, applying the results of [21], we obtain the PGF, denoted by $P_q(z)$, for P_j as follows:

$$\begin{aligned} P_q(z) &= \sum_{j=0}^{\infty} P_j z^j \\ &= \frac{(1-\Psi(z))P^+(z)}{\overline{y}\rho(1-z)\Psi(z)} \\ &= \frac{\left[\sum_{i=0}^{n} y_i \left(\sum_{j=0}^{i} P_j^+ + \sum_{j=1}^{\infty} P_{j+1}^+ z^j\right)\right]}{\overline{y}\rho(1-z)} \end{aligned} \tag{37}$$

Also, we derive the equilibrium-state probability P_j as follows:

$$P_j = \begin{cases} \frac{\sum_{i=0}^{n} y_i \sum_{k=0}^{i} P_k^+ - P_0^+}{\overline{y}\rho}, & j=0 \\ \frac{\sum_{i=0}^{n} y_i P_{j+i}^+ - P_j^+}{\overline{y}\rho} + P_{j-1}, & j \ge 1 \end{cases} \tag{38}$$

where P_j^+ is derived by Eq. (35). If we denote the average number of packets that secondary users send during a time slot at the equilibrium state by N_s, then we obtain:

$$N_s = \begin{cases} \min\left\{N_q, \left\lfloor \frac{RT_{NP}}{\ell} \right\rfloor \lim_{\tau\to\infty} L_{RSP}(\tau)\right\}, & \text{for RSP} \\ \min\left\{N_q, \left\lfloor \frac{RT_{NP}}{\ell} \right\rfloor \lim_{\tau\to\infty} L_{NSP}(\tau)\right\}, & \text{for NSP} \end{cases} \tag{39}$$

where the distributions of $L_{RSP}(\tau)$ and $L_{NSP}(\tau)$ are characterized by Eqs. (15) and (18), respectively. Thus, we obtain the aggregate throughput, denoted by η, as follows:

$$\eta = \frac{E[N_s]\ell}{T_S}. \tag{40}$$

Since the average queue length, denoted by L_q, of the packets for any given secondary user is the first moment of N_q, we have

$$L_q = \frac{d}{dz}P_q(z)\bigg|_{z=1} = L^+ - \overline{y}\rho + \frac{\lambda^2\Psi^{(2)}(1)}{2\overline{y}\rho}, \tag{41}$$

where L^+ is derived by Eq. (36). According to Little's law, the queueing delay, denoted by W_q, for a given secondary user can be derived by

$$W_q = \frac{L_q T_S}{\lambda}, \tag{42}$$

where T_S is the length of the time slot. Thus, the average packet transmission delay, denoted by W_s, for a given secondary user is derived as:

$$W_s = W_q + E[V]T_S = \left(\frac{L_q}{\lambda} + u\right)T_s, \tag{43}$$

where $E[V]T_S$ is the service delay.

TABLE I
THE PARAMETERS FOR OUR PROPOSED SCHEMES.

RTS	44 Bytes	The length of RTS packet
CTS	38 Bytes	The length of CTS packet
ℓ	250 Bytes	The length of the data packet
T_{ms}	9 μs	Mini-slot interval
T_S	1.89 ms	The length of time slot
SIFS	15 μs	Short inter-frame space
DIFS	34 μs	DCF inter-frame space
p	0.01	The prob. of sending a packet
R	1 Mbps	Data rate of the licensed channel

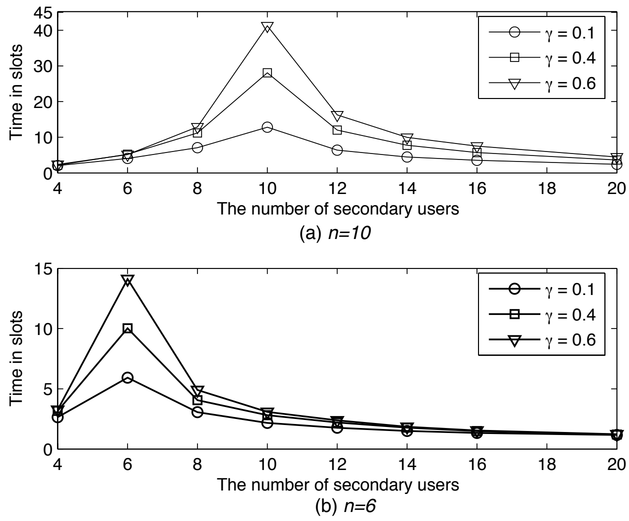

Fig. 6. The time spent to attain the desired state by the negotiation-based sensing policy against the number of secondary users with different γ's. (a) The case with $n = 10$. (b) The case with $n = 6$.

VI. Performance Evaluations

The parameters for our proposed schemes are summarized in Table I. These parameters ensure that Eq. (10) is satisfied, which suggests that at least one secondary user can successfully send RTS packet during the negotiating phase with a high probability.

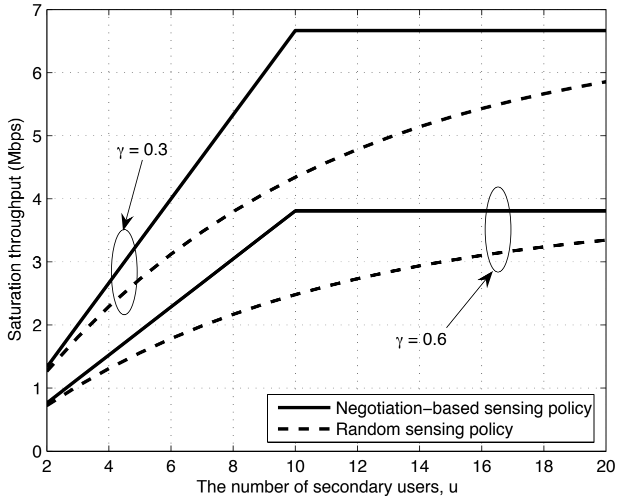

Fig. 7. The saturation throughput achieved by two different channel-sensing policies against the number (u) of secondary users with different γ's when the number (n) of licensed channels is 10.

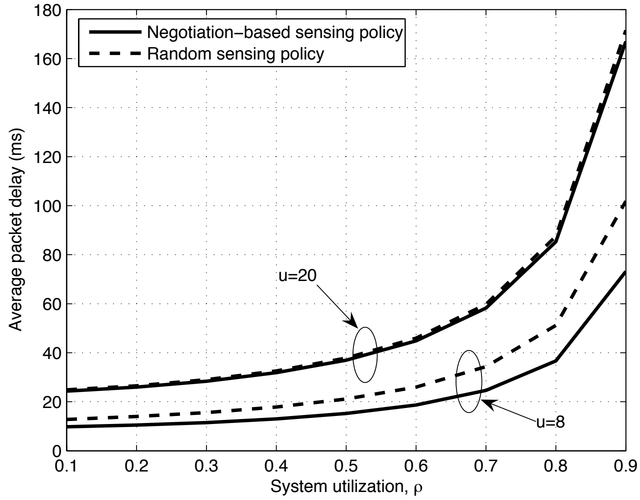

Fig. 8. The average packet transmission delay (W_s) against the system utilization (ρ) of secondary users with different number of secondary users (u) when the channel utilization (γ) of primary users is 0.6. The number (n) of licensed channels is 5. The solid lines represent the average packet transmission delay under negotiation-based sensing policy, and the dashed lines stand for the average packet transmission delay under the random sensing policy.

We first investigate the time spent by the negotiation-based sensing policy to attain the desired state, where 1) if the number (u) of secondary users is larger or equal to the number (n) of licensed channels, all the channels are sensed by the secondary users, 2) otherwise, each channel is sensed by no more than one secondary user. Fig. 6 plots the time spent to attain the desired state against the number of secondary users with different γ's and n's. Each point in Fig. 6 is the mean of the results of 500 simulations. Note that the length of the time slot is typically very short.[2] The negotiation-based sensing policy can quickly attain the desired state even in the worst case where $n = 10$ with $\gamma = 0.6$, as shown in Fig. 6. We also observe that the time spent to attain the desired state gets longer if the number u of secondary users becomes closer to the number n of channels. This is because i) when u is much smaller than n, it is less likely that the channels sensed by two secondary users are the same in the initial state, which will only take several more steps (in slots) to attain the desired state; and ii) when u is much larger than n, Fact 2 shows that most channels are sensed by the secondary users in the initial state, which is also close to the desired state. In addition, we notice that it will take more time to attain the desired state if the channel utilization (γ) by the primary users gets larger.

By using the analytical model developed in Section IV-B, we obtain the numerical results for the *saturation throughput* achieved by two different channel-sensing policies under different situations with $n = 10$, as shown in Fig. 7. Given γ and u, the saturation throughput achieved by the negotiation-based sensing policy is higher than that by the random sensing policy. When the number of secondary users is equal to the number of channels, the improvement achieved by the negotiation-based sensing policy over that achieved by the random sensing policy reaches to the maximum. When the number of secondary users is less than the number of channels, the saturation throughput achieved by the negotiation-based sensing policy increases linearly as the number of secondary users increases. However, the saturation throughput achieved by the negotiation-based sensing policy becomes the constant after the number of secondary users is larger than the number of channels. This is expected because all the leftover channels are perceived by the secondary users when the number of secondary users is larger than or equal to the number of channels, as discussed in Section III-C. From Fig. 7, we also observe that the larger the channel utilization by the primary users (γ), the lower saturation throughput the secondary users can achieve for both channel sensing policies, which makes sense because the higher the channel utilization (γ), the less the channels can be used by the secondary users.

Now, we investigate the performance of our proposed MAC protocols in the *non-saturation network* case, where the number (n) of licensed channels is set to 5. Using Eqs. (41) through (43), Fig. 8 plots the average packet transmission delay against the system utilization (ρ) of secondary users when the number of secondary users (u) is set to 8 and 20, respectively, while the channel utilization (γ) of primary users is fixed at 0.6. As the system utilization increases, the average packet transmission delay gets larger for both the negotiation-based sensing policy and the random sensing policy. Also, the average packet transmission delay increases much faster when the system utilization ρ gets larger. From Fig. 8, we observe that the average packet transmission delay achieved by the negotiation-based sensing policy is smaller than that achieved by the random sensing policy for the same ρ and u. In particular, when the number of secondary users is close to the number of licensed channels, the delay achieved by the negotiation-based sensing policy is much smaller than that achieved by the random sensing policy. However, the delays achieved by the negotiation-based sensing policy and the random sensing policy are virtually the same when the

[2]For example, the time-slot length of GSM cellular network is 577 μs.

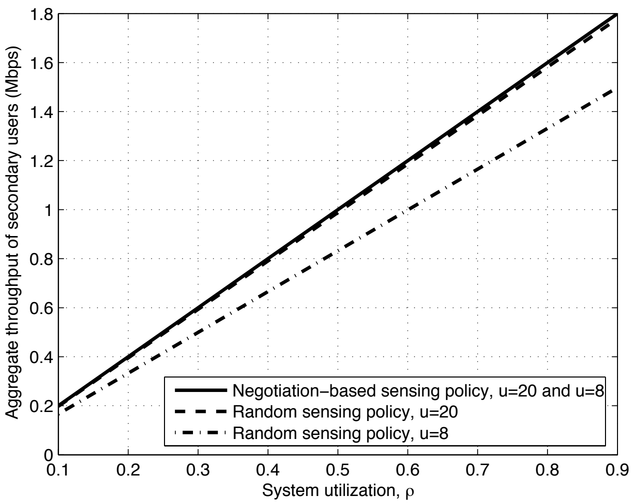

Fig. 9. The aggregate throughput (η) of secondary users against different system utilization (ρ) of secondary users when the number (u) of secondary users is equal to 20 and 8. The channel utilization (γ) of primary users is 0.6, and the number (n) of licensed channels is 5. The solid line represents the negotiation-based sensing policy for both $u = 8$ and $u = 20$, the dashed line represents the random sensing policy with $u = 20$, the dashdotted line represents the random sensing policy with $u = 8$.

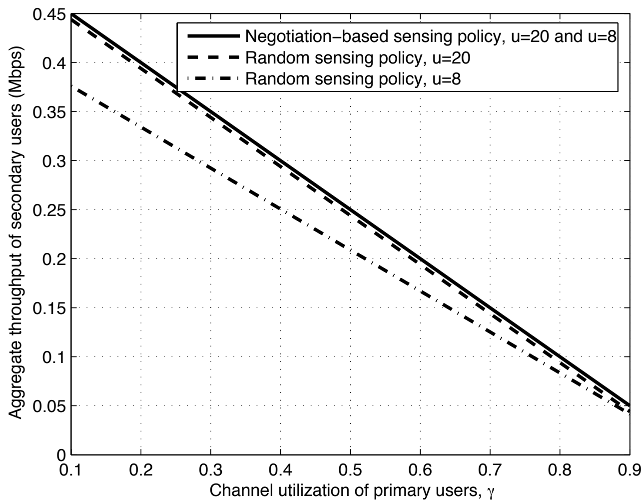

Fig. 11. The aggregate throughput (η) of secondary users varies with different channel utilization (γ) of primary users when the number (u) of secondary users is equal to 20 and 8. The system utilization (ρ) of secondary users is 0.1 and the number (n) of licensed channels is 5. The solid line represents the negotiation-based sensing policy for both $u = 8$ and $u = 20$, the dashed line represents the random sensing policy with $u = 20$, the dashdotted line represents the random sensing policy with $u = 8$.

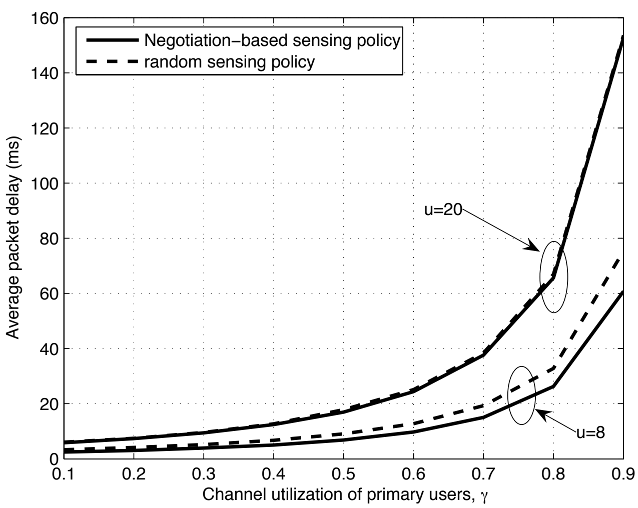

Fig. 10. The average packet transmission delay (W_s) against the channel utilization (γ) of primary users with different number of secondary users (u) when the system utilization (ρ) of secondary users is 0.1. The number (n) of licensed channels is 5. The solid lines represent the negotiation-based sensing policy, and the dashed lines stand for the random sensing policy.

number of secondary users is much larger than the number of licensed channels, which verifies Fact 2.

Using Eq. (40), Fig. 9 plots the aggregate throughput against the system utilization under both the negotiation-based sensing policy and random sensing policy. Note that under the negotiation-based sensing policy the aggregate throughput of $u = 20$ is the same as that of $u = 8$. This is because based on the negotiation-based sensing policy, the secondary users are aware of all channels' states in both $u = 20$ and $u = 8$ cases, and thus these two cases have the same total packet arrival rates under the same system utilization. The aggregate throughput increases linearly with the system utilization. The reason is that under the fixed γ, the increase of the system utilization (ρ) leads to the increase of the packet arrival rate (λ), which implies that more packets are sent under the non-saturation network case. From Figs. 8 and 9, we observe that there is a tradeoff between the aggregate throughput and average packet transmission delay. That is, as the system utilization increases, the aggregate throughput increases, while the average packet transmission delay also becomes larger.

Now, we investigate the impact of the channel utilization (γ) of the primary users on the performance of our proposed MAC protocols. Using Eqs. (41)-(43) and Eq. (40), Figs. 10 and 11 plot the average packet transmission delay against the channel utilization (γ) of the primary users and the aggregate throughput of the secondary users against the channel utilization of primary users, respectively. The system utilization (ρ) of secondary users is set as an constant of 0.1. The number (n) of licensed channels is set to 5. From Fig. 10, we observe that the average packet transmission delay increases monotonically with γ. The increasing rate of the average packet transmission delay becomes larger as the channel utilization (γ) of primary users increases. From Fig. 11, we find that the aggregate throughput decreases as the channel utilization of primary users increases. That is expected because the number of leftover licensed channels which can be utilized by the secondary users decreases, as the channel utilization of primary users gets larger. When the number of secondary users is small, the performance improvement of the negotiation-based sensing policy over the random sensing policy gets larger in terms of throughput and delay. On the other hand, when the number of secondary users gets large, the performance achieved by the simple random sensing policy is very close to that achieved by the negotiation-based sensing policy.

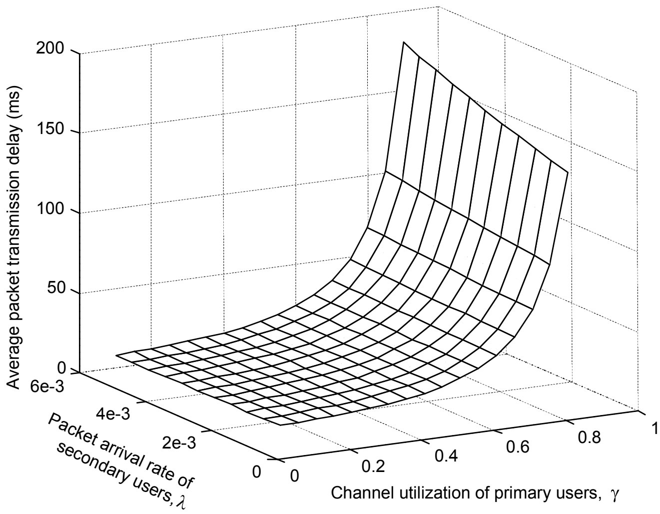

Fig. 12. The average packet transmission delay (W_s) varies with different γ's and λ's under negotiation-based sensing policy. The number (n) of licensed channels is 5 and the number (u) of secondary users is 20.

Using Eqs. (41)-(43), Fig. 12 plots the impact of different combinations of γ and λ on the average packet transmission delay under the negotiation-based sensing policy, when the number (n) of licensed channels is 5 and the number (u) of secondary users is 20. Under the same channel utilization of primary users, the higher the packet arrival rate, the larger the packet transmission delay. Furthermore, the impact of the packet arrival rate on the packet transmission delay gets higher when the channel utilization of primary users becomes larger. When the channel utilization of primary users is high, even the small increase of packet arrival rate can result in the significant increase of packet transmission delay. These observations provide practically important guidelines to derive the different desired parameters, such as packet arrival rate, the channel utilization of primary users, and the number of secondary users, etc., for the QoS-provisioning over the cognitive radio wireless networks.

VII. Conclusions

We proposed and analyzed the opportunistic multi-channel MAC protocols for the cognitive radio-based wireless ad hoc networks. Specifically, the cognitive MAC protocols enable the secondary users to identify and utilize the available frequency spectrum without causing harmful interference to the primary users. To detect the availabilities of the un-used licensed channels, we proposed two different channel sensing policies: the random sensing policy and the negotiation-based sensing policy. Our proposed cognitive radio-based MAC protocols do not need any centralized controllers, since the negotiation between the sender and receiver of the secondary users is conducted using the CSMA/CA-based algorithm. Applying the Markov chain model and the $M/G^Y/1$ queueing model, we develop analytical models to evaluate the performance of our proposed protocols with two channel sensing policies for both the saturation network case and non-saturation network case, respectively. Our analyses also reveal the tradeoff between throughput and delay, which provides the guidelines to support the different QoS requirements over cognitive radio based wireless networks.

Appendix

A. The proof of Proposition 1

Proof: To prove the proposition, we only need to show that $|B_0(t) \cup B_1(t)| \leq |B_0(t+1) \cup B_1(t+1)|$ holds for any given time slot, indexed by t with $t = 0, 1, 2, \cdots$. We need to consider the following three cases. First, all the secondary users fail to send RTS/CTS packets during the negotiating phase in t-th time slot. None of them will change the channel to sense in the $(t+1)$-th time slot. This implies that the number of sensed channels in the $(t+1)$-th time slot stays the same as that in t-th time slot, i.e., $|B_0(t) \cup B_1(t)| = |B_0(t+1) \cup B_1(t+1)|$. Second, a given secondary user successfully sends the RTS/CTS packets. There is no other secondary users which sense the same channel as this given secondary user. In this case, no secondary users will change their sensing channels in the $(t+1)$-th time slot, implying that $|B_0(t) \cup B_1(t)| = |B_0(t+1) \cup B_1(t+1)|$ holds. Third, a given secondary user successfully transmits the RTS/CTS packets during the negotiating phase and the channel sensed by this given secondary user is sensed by at least another different one or more of secondary users. In this case, the other different secondary user(s) must select different channel(s) from the set of $(B_1(t) \cup B_2(t))$ for sensing in the $(t+1)$-th time slot. Consequently, the channels in $B_2(t)$ can be selected as well, implying that $|B_2(t)| \geq |B_2(t+1)|$, and thus $|B_0(t) \cup B_1(t)| \leq |B_0(t+1) \cup B_1(t+1)|$. According to the above three cases, $|B_0(t) \cup B_1(t)| \leq |B_0(t+1) \cup B_1(t+1)|$ always holds, completing the proof. ∎

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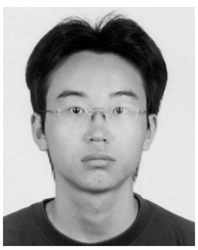

Hang Su received B.S. and M.S. degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 2002 and 2005, respectively. He is currently a research assistant working toward a Ph.D. degree at the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station. He worked as a software engineer with Nokia Research Center, Hangzhou, China, in 2005.

His research interests lie in cognitive radio-based networks, vehicular ad hoc networks, and wireless sensor networks with emphasis on design and analysis of MAC and routing protocols.

Xi Zhang (S'89-SM'98) received the B.S. and M.S. degrees from Xidian University, Xi'an, China, the M.S. degree from Lehigh University, Bethlehem, PA, all in electrical engineering and computer science, and the Ph.D. degree in electrical engineering and computer science (Electrical Engineering-Systems) from The University of Michigan, Ann Arbor.

He is currently an Assistant Professor and the Founding Director of the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station. He was an Assistant Professor and the Founding Director of the Division of Computer Systems Engineering, Department of Electrical Engineering and Computer Science, Beijing Information Technology Engineering Institute, Beijing, China, from 1984 to 1989. He was a Research Fellow with the School of Electrical Engineering, University of Technology, Sydney, Australia, and the Department of Electrical and Computer Engineering, James Cook University, Queensland, Australia, under a Fellowship from the Chinese National Commission of Education. He worked as a Summer Intern with the Networks and Distributed Systems Research Department, AT&T Bell Laboratories, Murray Hills, NJ, and with AT&T Laboratories Research, Florham Park, NJ, in 1997. He has published more than 100 research papers in the areas of wireless networks and communications, mobile computing, cross-layer optimizations for QoS guarantees over mobile wireless networks, effective capacity and effective bandwidth theories for wireless networks, DS-CDMA, MIMO-OFDM and space-time coding, adaptive modulations and coding (AMC), wireless diversity techniques and resource allocations, wireless sensor and Ad Hoc networks, cognitive radio and cooperative communications/relay networks, vehicular Ad Hoc networks, multi-channel MAC protocols, wireless and wired network security, wireless and wired multicast networks, channel coding for mobile wireless multimedia multicast, network protocols design and modeling, statistical communications theory, information theory, random signal processing, and control theory and systems.

Prof. Zhang received the U.S. National Science Foundation CAREER Award in 2004 for his research in the areas of mobile wireless and multicast networking and systems. He received the TEES Select Young Faculty Award for Excellence in Research Performance from the Dwight Look College of Engineering at Texas A&M University, College Station, in 2006. He also received the Best Paper Award in the IEEE Globecom 2007. He is currently serving as an Editor for the serving as an Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, an Associate Editor for the IEEE COMMUNICATIONS LETTERS, an Editor for the WILEY'S JOURNAL ON WIRELESS COMMUNICATIONS AND MOBILE COMPUTING, an Editor for the JOURNAL OF COMPUTER SYSTEMS, NETWORKING, AND COMMUNICATIONS, and an Associate Editor for the JOHN WILEY'S JOURNAL ON SECURITY AND COMMUNICATIONS NETWORKS, and is also serving as the Guest Editor for for the special issue on "next generation of CDMA versus OFDMA for 4G wireless applications". He has frequently served as the Panelist on the U.S. National Science Foundation Research-Proposal Review Panels. He is serving or has served as the Co-Chair for the IEEE Globecom 2008 – Wireless Communications Symposium and the Co-Chair for the IEEE ICC 2008 – Information and Network Security Symposium, respectively, the Symposium Chair for the IEEE/ACM International Cross-Layer Optimized Wireless Networks Symposium 2006, 2007, and 2008, respectively, the TPC Chair for the IEEE/ACM IWCMC 2006, 2007, and 2008, respectively, the Poster Chair for the IEEE INFOCOM 2008, the Student Travel Grants Co-Chair for the IEEE INFOCOM 2007, the Panel Co-Chair for the IEEE ICCCN 2007, the Poster Chair for the IEEE/ACM MSWiM 2007 and the IEEE QShine 2006, the Publicity Chair for the IEEE/ACM QShine 2007 and the IEEE WirelessCom 2005, and the Panelist on the Cross-Layer Optimized Wireless Networks and Multimedia Communications at IEEE ICCCN 2007 and WiFi-Hotspots/WLAN and QoS Panel at the IEEE QShine 2004. He has served as the TPC members for more than 50 IEEE/ACM conferences, including the IEEE INFOCOM, IEEE Globecom, IEEE ICC, IEEE WCNC, IEEE VTC, IEEE/ACM QShine, IEEE WoWMoM, IEEE ICCCN, etc.

Prof. Zhang is a Senior Member of the IEEE and a Member of the Association for Computing Machinery (ACM).