Full-Duplex Spectrum-Sensing and MAC-Protocol for Multichannel Nontime-Slotted Cognitive Radio Networks

Wenchi Cheng, Xi Zhang, *Senior Member, IEEE*, and Hailin Zhang, *Member, IEEE*

***Abstract*—Because of the asynchronization between primary and secondary wireless networks, the synchronization between primary users (PUs) and secondary users (SUs) can be hardly guaranteed in nontime-slotted cognitive radio networks (CRNs). In this paper, we propose a novel framework for multichannel nontime-slotted CRNs, where the PUs randomly access and leave the licensed channels. Since the PUs cannot distinguish between primary and secondary signals, the PUs may sense a busy channel when the PUs start to reactivate during the SUs' transmission, thus generating a collision or entering the backoff stage. To guarantee the high-throughput transmission of the PUs and increase the channel utilization of the SUs, in this paper, we propose the wireless full-duplex spectrum sensing (FD-SS) scheme for SUs in multichannel nontime-slotted CRNs. Using our developed FD-SS scheme, the SUs can timely sense the PUs' reactivation during the same time when the SUs are transmitting their signals. Then, based on our proposed wireless FD-SS scheme, we further develop and analyze the wireless full-duplex cognitive medium access control (FDC-MAC) protocol for multichannel nontime-slotted CRNs. We conduct extensive numerical analyses, showing that our developed FD-SS scheme and FDC-MAC protocol can efficiently guarantee the high-throughput transmission of the PUs and increase the channel utilization of the SUs without requiring the synchronization between the PUs and the SUs over the multichannel nontime-slotted CRNs.**

***Index Terms*—Cognitive radio networks (CRNs), multichannel non-time-slotted CRNs, MAC protocol, full-duplex spectrum sensing.**

I. Introduction

COGNITIVE RADIO NETWORKs (CRNs), where the secondary users (SUs) dynamically utilize the idle licensed channels of primary users (PUs), can achieve high spectrum utilization and improve the quality of wireless applications [1], [2]. In CRNs, the SUs sense the states of the PUs and use the licensed channels when they are not occupied by the PUs. The PUs and the SUs form the primary wireless network and the secondary wireless network, respectively. To efficiently sense the PUs, it is desirable that the secondary wireless network is synchronized with the primary wireless network [3], [4].

Most existing works focus on the time-slotted CRNs where the PUs and the SUs are synchronized [5]–[9]. In time-slotted CRNs, the PUs will only change their states (from active state to inactive state or from inactive state to active state) at the beginning of each time-slotted frame. Therefore, once the SUs attempt to transmit their data, they can sense the licensed channel during a short sensing period and transmit their data during the transmission period if they sensed that the licensed channels are idle. A great deal of researches have been done to improve the performance of time-slotted CRNs. In [5], the authors analyzed the decision of SUs to sense and access channels using a partially observable Markov decision process framework. In [6], the authors formulated the sensing-throughput tradeoff problem and used energy detection sensing scheme to prove that the formulated problem indeed has one optimal sensing period which yields the highest throughput for the secondary wireless network. The authors of [7] developed an optimal spectrum sensing framework to solve both the interference avoidance and the spectrum efficiency problem. Under the control of dedicated channel, the authors of [8], [9] proposed the cognitive medium access control (MAC) protocols to increase the SUs' throughput in time-slotted CRNs.

However, the primary wireless network and the secondary wireless network are often two different types of wireless networks. The secondary network is often implemented when the primary network had been set up for a long time. It is difficult or expensive to guarantee the synchronization between the PUs and the SUs. For example, in IEEE 802.22 [10], the primary wireless network is the television wireless network and the secondary wireless network is the wireless regional area network. Therefore, it is more practical to consider the asynchronization between the PUs and the SUs in CRNs. We define the *non-time-slotted CRNs* as the wireless cognitive radio network where the PUs and the SUs are asynchronous.

In this paper, we consider the multichannel non-time-slotted CRNs, where the primary wireless network and the secondary wireless network are asychronous. Because of the asynchronization between the PUs and the SUs, the PUs may sense a busy channel when the PUs are going to reactivate during the SUs' transmission, thus generating a collision or entering the backoff stage, which is the reactivation-failure problem. The

Manuscript received January 5, 2014; revised May 15, 2014; accepted June 20, 2014. Date of publication September 30, 2014; date of current version April 21, 2015. This work of Xi Zhang was supported in part by the U.S. National Science Foundation under Grants ECCS-1408601 and CNS-1205726. This work of Wenchi Cheng and Hailin Zhang was supported in part by the National Natural Science Foundation of China (No. 61401330), the 111 Project of China (B08038), and the Important National Science and Technology Specific Projects (2013ZX03003008).

X. Zhang is with the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: xizhang@ece.tamu.edu) (Corresponding Author).

W. Cheng and H. Zhang are with the State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an, 710071, China (e-mail: wccheng@xidian.edu.cn; hlzhang@xidian.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSAC.2014.2361078

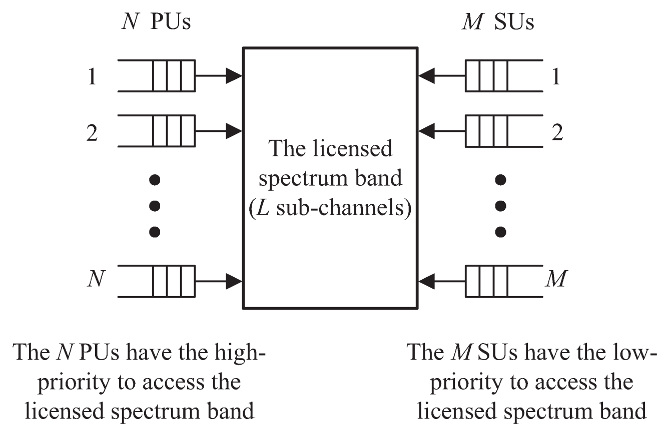

Fig. 1. The multichannel cognitive radio network model.

traditional half-duplex-based spectrum sensing schemes [5]–[7] and the half-duplex-based MAC protocols [8], [9] cannot solve the reactivation-failure problem for non-time-slotted CRNs. To efficiently implement the non-time-slotted CRNs, in this paper, we develop the wireless full-duplex spectrum sensing (FD-SS) scheme and the wireless full-duplex cognitive MAC (FDC-MAC) protocol, which show the way that how to effectively overcome the reactivation-failure problem in multichannel non-time-slotted CRNs.

The rest of this paper is organized as follows. Section II describes the system model. Section III proposes the wireless FD-SS scheme for SUs to sense the PUs' reactivation during the same time when the SUs are transmitting their signals. Based on the proposed wireless FD-SS scheme, Section IV develops the wireless FDC-MAC protocol and analyzes the throughput of using our developed wireless FDC-MAC protocol for multichannel non-time-slotted CRNs. Section V evaluates our developed wireless FD-SS scheme and wireless FDC-MAC protocol for multichannel non-time-slotted CRNs. The paper concludes with Section VI.

II. The System Model

We consider a licensed spectrum band with L sub-channels which are licensed to a primary wireless network consisting of N PUs, as shown in Fig. 1, where the sub-channels are implemented by the same frequency bands and time-slots. The PUs have the high-priority to access the licensed sub-channels. When a primary user wants to initiate a transmission, it follows the p-persistent Carrier Sense Multiple Access (CSMA) protocol [11] to access the licensed sub-channels. To efficiently utilize the spare spectrum, M SUs with the low-priority queue seek idle spectrum opportunities in the licensed spectrum band. The SUs also follow the p-persistent CSMA protocol to avoid the confliction. The PUs and the SUs form the primary wireless network and the secondary wireless network, respectively.

A. The Non-Time-Slotted Cognitive Radio Networks Control Model

The non-time-slotted cognitive radio network is defined as the wireless cognitive radio network where the PUs and the SUs are asynchronous. Fig. 2(a) shows the timing control sequences of PUs and SUs in non-time-slotted CRNs, where the PUs randomly access and leave the licensed sub-channels. The PUs follow the non-time-slotted structure while the SUs can be designed to follow the time-slotted structure. The PUs' state transition is asynchronous with the time-slotted frame of SUs. To compare the non-time-slotted CRNs with the time-slotted CRNs, Fig. 2(b) illustrates the time-slotted PUs and the time-slotted SUs in time-slotted CRNs, where the PUs' state transition is synchronized with the time-slotted frame of SUs. Comparing Fig. 2(a) and Fig. 2(b), it is clear that the SUs can be synchronized with the PUs in time-slotted CRNs (Fig. 2(b)) while the SUs cannot be synchronized with the PUs in non-time-slotted CRNs (Fig. 2(a)).

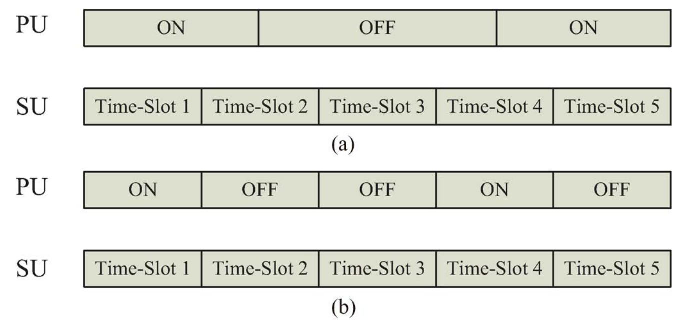

Fig. 2. Comparison between the non-time-slotted CRNs and the time-slotted CRNs. (a) The non-time-slotted PU and the time-slotted SU in non-time-slotted CRNs. (b) The time-slotted PU and the time-slotted SU in time-slotted CRNs.

B. Reactivation-Failure Problem in Multichannel Non-Time-Slotted CRNs

In our defined multichannel non-time-slotted CRNs, the PUs and the SUs follow the p-persistent CSMA protocol. Under the p-persistent CSMA protocol, if the channel is detected as busy, the user (PU or SU) with a non-empty queue waits until channel becomes idle, and then transmits the packet with probability p. Therefore, not only the SUs, but also the PUs need to listen to the licensed channel to avoid the confliction. This scenario is more practical than the scenarios in most exiting CRNs, where the contention among PUs [5]–[9] is often ignored.

Ignoring the contention among PUs does not impact the performance of time-slotted CRNs. In time-slotted CRNs, because the PUs and SUs are synchronized, the PUs only change their states at the start of each time-slotted frame of SUs. Thus, the SU, which is using the idle licensed channel, can sense the PU's reactivation during the very short sensing period. However, for non-time-slotted CRNs, ignoring the contention among PUs will severely deteriorate the performance of primary networks. Fig. 3 shows the reactivation-failure problem in multichannel non-time-slotted CRNs. As shown in Fig. 3, in non-time-slotted CRNs, the PU may reactivate to use the licensed channel when the SU is using the idle channel. Since the PUs is not aware of existence of SUs and thus do not know whether the licensed channel is currently used by a PU or an SU, the PUs will "think" the licensed channel is occupied by another peer PU, thus entering the backoff stage. Because the transmission period of the SU is much longer than the sensing period of the SU [6], the

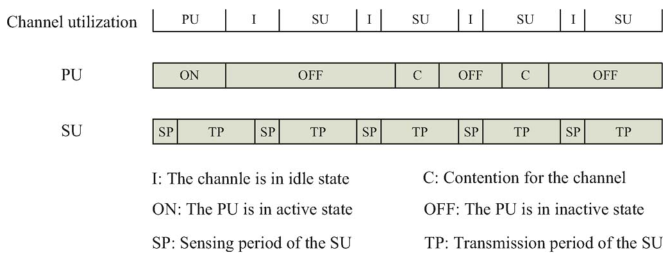

Fig. 3. The reactivation-failure problem in multichannel non-time-slotted CRNs.

PU may always sense that the licensed channel is occupied by a peer PU. This will delay the reactivation of the PU. If the delay exceeds the maximum tolerant delay of the primary traffic, the primary data will be discarded, thus seriously impacting the performance of primary wireless networks. If the performance of primary wireless networks cannot be guaranteed, it is meaningless to implement the multichannel non-time-slotted CRNs.

We call the incident that the SU cannot detect the PU's reactivation as the *reactivation-failure problem*. The reactivation-failure problem is a very critical problem in multichannel non-time-slotted CRNs. If the reactivation-failure problem cannot be overcome, the required throughput of PUs cannot be guaranteed in the multichannel non-time-slotted CRNs. Under this circumstance, no matter how high the achieved throughput for SUs, the multichannel non-time-slotted CRNs are not in normal operating status. Therefore, to efficiently implement the multichannel non-time-slotted CRNs, we need to overcome the reactivation-failure problem.

C. Spectrum Sensing in Multichannel Non-Time-Slotted CRNs

It has been analyzed and evaluated that the traditional wireless half-duplex spectrum sensing schemes are efficient in time-slotted CRNs [6], [7]. When the PUs only access the channel at the start of time-slotted frames of SUs, the traditional wireless half-duplex spectrum sensing schemes can guarantee the required throughput for PUs and maximize the achieved throughput for SUs in time-slotted CRNs.

However, in multichannel non-time slotted CRNs, the PUs randomly access and leave the licensed channel. The wireless half-duplex spectrum sensing schemes cannot solve the reactivation-failure problem as shown in Fig. 3. As illustrated in Fig. 3, with the traditional wireless half-duplex spectrum sensing (for example, the wireless half-duplex-based energy detection spectrum sensing scheme proposed in [6]), the SU can sense the idle sub-channel using the short sensing period. Then, the SU occupies the sub-channel. However, because of the asynchronization between the PUs and the SUs, the PU's contention for reactivation in the licensed sub-channel may conflict with the SU's transmission. Therefore, with the wireless half-duplex spectrum sensing schemes, it is impossible to solve the reactivation-failure problem in multichannel non-time-slotted CRNs. We need to develop the efficient spectrum sensing scheme to solve the reactivation-failure problem in multichannel non-time-slotted CRNs.

In the following we first develop the wireless full-duplex spectrum sensing (FD-SS) scheme for multichannel non-time-slotted CRNs. Using the wireless FD-SS scheme, the SU can sense the PU's reactivation during the same time when the SU is transmitting its signal. Then, based on the developed wireless FD-SS scheme, we further develop the wireless FDC-MAC protocol to solve the reactivation-failure problem in multichannel non-time-slotted CRNs.

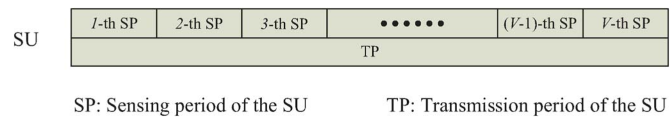

Fig. 4. The division of one time-slotted frame (TP) of SUs into V sensing periods (SP), where $\mathrm{SP} \ll \mathrm{TP}$.

III. Wireless Full-Duplex Spectrum Sensing Scheme

Several signal detection techniques, such as the energy detection, feature detection, and matched filter, can be used for the SUs to sense the presence of the PUs [12], [13]. We mainly focus on the energy detection approach because the energy detection approach is efficient and simple to be implemented in hardware. More importantly, the energy detection approach does not require the knowledge of signal features of the PUs, which typically may not be known to the SUs. Let $\mathcal{H}_{01}$ and $\mathcal{H}_{10}$ be the hypotheses that the PU changes from inactive state to active state and from active state to inactive state, respectively, during one sensing period of SUs.

To detect the random access and departure of the PUs, the SUs need to sense the licensed channel not only in the sensing period but also in the transmission period. To enable the SUs' sensing during the transmission period, the SUs need to use the wireless full-duplex mode with transmitting and sensing simultaneously. The wireless full-duplex communication mode has been verified to be implemented in practical wireless networks recently [14]–[20]. To sense the licensed sub-channels in the SUs' transmission period, we divide each time-slotted frame of SUs into V periods as shown in Fig. 4. Since the SUs use the wireless full-duplex mode, they can transmit data and sense the sub-channels simultaneously during the entire time-slotted frame. Then, we propose the wireless full-duplex spectrum sensing (FD-SS) scheme as follows (pseudo code):

Wireless FD-SS Scheme:

1) Divide each time-slotted frame of the SUs into V sensing periods;
2) **If** (the SU attempts to use the idle channel)
3) The SU randomly chooses sub-channels to sense using the traditional wireless half-duplex-based energy detection within each sensing period;
4) **Else if** (the SU is using the channel C_1)
5) The SU senses the channel C_1 using the wireless full-duplex-based energy detection within each sensing period;
6) **End if**

Under the wireless full-duplex mode, the PU's transmit signal received at the SU at time t, denoted by $r(t)$, can be written as follows:

$$r(t) = \sqrt{\kappa} h s(t) + \omega(t), \tag{1}$$

where h is the instantaneous amplitude gain of the channel between the PU and the SU, which follows Rayleigh distribution; $s(t)$ is signal sent by PU with transmit power E_s; $\omega(t)$ represents the additive white Gaussian noise (AWGN) with zero mean and variance of σ^2; $\kappa (0 < \kappa \leq 1)$ is the self-interference mitigation coefficient, defined as the impact of self-interference mitigation on the wireless full-duplex communication [21]. When κ approaches 0, it implies that the self-interference creates large interference on wireless full-duplex communication. When κ approaches 1, it indicates that the self-interference causes little interference on wireless full-duplex communication.

Then, we can write the test statistics of wireless full-duplex energy detection for the channel from the PU to the SU, denoted by $Y_N(r)$, as follows:

$$Y_N(r) = \begin{cases} \frac{1}{U}\left(\sum\limits_{m=0}^{d} |\sqrt{\kappa} h s(m) + \omega(m)|^2 + \sum\limits_{m=d+1}^{U} |\omega(m)|^2\right), & \text{if } \mathcal{H}_{10}; \\ \frac{1}{U}\left(\sum\limits_{m=0}^{a} |\omega(m)|^2 + \sum\limits_{m=a+1}^{U} |\sqrt{\kappa} h s(m) + \omega(m)|^2\right), & \text{if } \mathcal{H}_{01}, \end{cases} \tag{2}$$

where $\mathcal{H}_{10}$ implies that the primary is active for d samples and then becomes inactive, $\mathcal{H}_{01}$ implies that the primary is inactive for a samples and then becomes active, U is the number of samples for the entire sensing period. For the convenience of our following analysis, we assume that $s(0) = 0$ and $\omega(0) = 0$.

We consider the circularly symmetric complex Gaussian (CSCG) signal for the primary signal $s(m)$ and the noise $\omega(m)$. The CSCG signal represents signals with rich inter-symbol interference such as orthogonal frequency division multiplexing (OFDM) signals or OFDM signals with linear precoding. When U is relatively large, using the central limit theorem, under the hypothesis $\mathcal{H}_{10}$, the probability density function of $Y_N(r)$, denoted by $p_{10}(x)$, can be approximated by a Gaussian distribution [6]. Also, under hypothesis $\mathcal{H}_{01}$, the probability density function of $Y_N(r)$, denoted by $p_{01}(x)$, can be approximated by a Gaussian distribution. Thus, we can derive the probability of false alarm and the probability of detecting a PU for non-time-slotted CRNs as shown in the following Lemma 1.

Lemma 1: The probability of false alarm and the probability of detecting a PU for non-time-slotted CRNs, denoted by $p_f(\epsilon, U, d, \kappa)$ and $p_d(\epsilon, U, a, \kappa)$, respectively, are given by

$$\begin{aligned} p_f(\epsilon, U, d, \kappa) &= \Pr\{Y_N(r) > \epsilon | \mathcal{H}_{10}\} = \int_{\epsilon}^{\infty} p_{10}(x) dx \\ &= \mathcal{Q}\left(\frac{\frac{\epsilon}{\sigma_u^2} - \frac{d}{U}\kappa\gamma_{ps} - 1}{\sqrt{\frac{d}{U^2}(\kappa\gamma_{ps}+1)^2 + \frac{U-d}{U^2}}}\right) \end{aligned} \tag{3}$$

and

$$\begin{aligned} p_d(\epsilon, U, a, \kappa) &= \Pr\{Y_N(r) > \epsilon | \mathcal{H}_{01}\} = \int_{\epsilon}^{\infty} p_{01}(x) dx \\ &= \mathcal{Q}\left(\frac{\frac{\epsilon}{\sigma_u^2} - \frac{U-a}{U}\kappa\gamma_{ps} - 1}{\sqrt{\frac{U-a}{U^2}(\kappa\gamma_{ps}+1)^2 + \frac{a}{U^2}}}\right), \end{aligned} \tag{4}$$

respectively, where ϵ is the energy detection threshold and $\mathcal{Q}(x)$ is the complementary distribution function of the standard Gaussian, which can be written as follows:

$$\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt. \tag{5}$$

Proof: When the noise $\omega(n)$ is CSCG, for a large U, the probability density function (PDF) of $Y_N(r)$ under hypothesis $\mathcal{H}_{10}$ can be approximated by a Gaussian distribution with mean, denoted by u_0, as follows:

$$u_0 = \left(\frac{d}{U}\kappa\gamma_{ps} + 1\right)\sigma_u^2 \tag{6}$$

and variance, denoted by σ_0^2, as follows:

$$\sigma_0^2 = \frac{d}{U^2}(\kappa\gamma_{ps}+1)^2\sigma_u^4 + \frac{U-d}{U^2}\sigma_u^4, \tag{7}$$

where γ_{ps} and σ_u^2 are the received SNR at the SU and the variance of the noise.

Thus, we can derive the probability of false alarm as follows:

$$\begin{aligned} p_f&(\epsilon, U, d, \kappa) \\ &= \Pr\{Y_N(r) > \epsilon | \mathcal{H}_{10}\} \\ &= \int_{\epsilon}^{\infty} p_{10}(x)\, dx \\ &= \int_{\epsilon}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left(-\frac{(x-u_0)^2}{2\sigma_0^2}\right) dx \\ &= \int_{\epsilon}^{\infty} \frac{1}{\sqrt{2\pi}\sqrt{\frac{d}{U^2}(\kappa\gamma_{ps}+1)^2\sigma_u^4 + \frac{U-d}{U^2}\sigma_u^4}} \\ &\quad \times \exp\left(-\frac{\left(x - \left(\frac{d}{U}\kappa\gamma_{ps}+1\right)\sigma_u^2\right)^2}{2\left(\frac{d}{U^2}(\kappa\gamma_{ps}+1)^2\sigma_u^4 + \frac{U-d}{U^2}\sigma_u^4\right)}\right) dx. \end{aligned} \tag{8}$$

Defining the new function $\alpha(x)$ as follows:

$$\alpha(x) \triangleq \frac{x - \left(\frac{d}{U}\kappa\gamma_{ps}+1\right)\sigma_u^2}{\sqrt{\frac{d}{U^2}(\kappa\gamma_{ps}+1)^2\sigma_u^4 + \frac{U-d}{U^2}\sigma_u^4}}, \tag{9}$$

and plugging Eq. (9) into Eq. (8), we have

$$p_f(\epsilon, U, d, \kappa) = \frac{1}{\sqrt{2\pi}} \int_{\alpha(\epsilon)}^{\infty} \exp\left(-\frac{z^2}{2}\right) dz = \mathcal{Q}\left(\frac{\frac{\epsilon}{\sigma_u^2} - \frac{d}{U}\kappa\gamma_{ps} - 1}{\sqrt{\frac{d}{U^2}\left(\kappa\gamma_{ps}+1\right)^2 + \frac{U-d}{U^2}}}\right) \tag{10}$$

which is Eq. (3). In the similar way, we can derive Eq. (4). Thus, Lemma 1 follows. ■

Setting $a=0$, $d=0$, and $\kappa=1$ in Eqs. (3) and (4), we can obtain the probability of false alarm $p_f(\epsilon, U, 0, 1)$ and the probability of detection $p_d(\epsilon, U, 0, 1)$ as follows:

$$\begin{cases} p_f(\epsilon, U, 0, 1) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - 1\right)\sqrt{U}\right); \\ p_d(\epsilon, U, 0, 1) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - \gamma_{ps} - 1\right)\frac{\sqrt{U}}{\gamma_{ps}+1}\right). \end{cases} \tag{11}$$

Comparing the probability of false alarm for the non-time-slotted CRN with the probability of false alarm for the time-slotted CRN, we observe that when $d=0$ and $\kappa=1$ the probability of false alarm for the non-time-slotted CRN reduces to the probability of false alarm for the time-slotted CRN [6], [22]. Also comparing the probability of detection for the non-time-slotted CRN with the probability of detection for the time-slotted CRN, we observe that the probability of detection for the non-time-slotted CRN reduces to the probability of detection for the time-slotted CRN [6], [22] when $a=0$ and $\kappa=1$. This implies that the time-slotted CRN is a special case of the non-time-slotted CRN.

IV. Wireless Full-Duplex Cognitive MAC Protocol

A. *The Wireless Full-Duplex Cognitive (FDC) MAC Protocol Overview*

To efficiently support the multichannel non-time-slotted CRNs, we need to develop the wireless full-duplex cognitive MAC (FDC-MAC) protocol, which is based on the developed wireless FD-SS scheme. The wireless FDC-MAC protocol needs to support the PUs' reactivation during the same time when the SUs are transmitting their signals. Each SU transmits the request-to-send (RTS) packet with probability p. After the SU successfully receives clear-to-send (CTS) packet since sending the last RTS, it gets the permission to transmit data packets in the coming next time slot.

The pseudo code of our developed wireless FDC-MAC protocol for multichannel non-time-slotted CRNs is given as follows (I is the identifier with $I \in \{0, 1\}$ denoting whether there exits an idle sub-channel ($I=1$) or not ($I=0$); Q is the queue length of the SU):

Wireless FDC-MAC protocol for each SU in multichannel non-time-slotted CRNs:

1) **While** $(Q \neq 0)$
2) **If** (the SU attempts to find an idle sub-channel)
3) $I=0, i=1;$
4) While $(I=0)$;
5) The SU senses the $(i \bmod L)$-th sub-channel using the wireless FD-SS scheme;
6) **If** (the $(i \bmod L)$-th sub-channel is sensed as idle)
7) $I=1;$
8) $C_2 = (i \bmod L);$
9) **If** $((i \bmod L) = 0)$
10) $C_2 = L;$
11) **End if**
12) **Else**
13) $i = i+1;$
14) **End if**
15) **End while**
16) The SU transmits the request-to-send (RTS) packet with probability p.
17) **If** (the SU successfully receives clear-to-send (CTS) packet)
18) The SU gets the permission to transmit data packets using the sub-channel C_2;
19) **End if**
20) **Else** %The SU is transmitting using a sub-channel, which is denoted by C_2.
21) The SU senses the sub-channel C_2 using the wireless FD-SS scheme;
22) **If** (the sub-channel C_2 is sensed as idle)
23) The SU keeps transmission using the sub-channel C_2;
24) **Else** %The sub-channel C_2 is sensed as busy.
25) The SU stops transmission with the sub-channel C_2 and attempts to find *another* idle sub-channel;[1] %For the contention fairness among SUs.
26) **End if**
27) **End if**
28) **End while**

With our developed wireless FDC-MAC protocol, if the SU attempts to find an idle sub-channel to transmit its own data, it cyclically senses each sub-channel until it finds an idle sub-channel. If the SU is using an idle sub-channel C_2,

[1] Under our full-duplex mode with the CSMA protocol, when an SU occupying the licensed channel senses the new active SUs contending for the channel at the end of current SP, this SU must stop participating in competition for this channel again with the other active SUs in the very next SP. This way, the competition for the licensed channel among SUs can be kept to be fair because each SU is prevented from using the channel consecutively in more than one SPs when there are multiple active SUs competing for the channel. On the other hand, the highly frequent sensing of the new requests for the licensed channel request from SUs during each short SP time interval imposes the extra sensing energy cost which is the expenses paid for SUs' contention-fairness gain achieved.

it keeps sensing the sub-channel C_2. Once detected the PU's reactivation under the wireless FD-SS scheme, the SU stops transmission with the sub-channel C_2 immediately, and then tries to find another idle sub-channel to go on its transmission. Thus, with our developed wireless FDC-MAC protocol, each SU can not only acquire the idle sub-channel when the SU attempts to transmit its own data, but also overcome the reactivation-failure problem of PUs, which is very crucial for multichannel non-time-slotted CRNs.

In particular, our proposed RTS/CTS MAC protocol can significantly mitigate this PUs' reactivation-failure problem (due to the mutual impact between PUs and SUs) by increasing the detection frequency with a number (V) of short sensing periods (SP), where SP $\ll$ TP (see Fig. 4 and its caption). Using our proposed FDC-MAC protocol, even if an SU (among the SUs which attempt to access the licensed channel with the PU at the same time) wins the competition for the licensed channel over a PU, it still can sense the PU's reactivation at the very next short sensing period (SP). Then, SUs can return the licensed channel back to the PU at the end of the very next short sensing period (SP) to overcome the reactivation-failure problem.

B. Throughput Analyses of the Wireless FDC-MAC Protocol for the Saturation Network Case

In this section, we consider the saturation network case, where each SU always has the non-empty queue and contends for sending the request-to-send (RTS) packets by using p-persistent CSMA. We develop an analytical model to analyze the throughput of our proposed wireless FDC-MAC protocol for the saturation network case. Under the p-persistent CSMA protocol, if the channel is detected as busy, the SU with a non-empty queue waits until channel becomes idle, and then transmits the packet with probability p.

Then, we study the achievable throughput of the PUs and the SUs. We assume that the channel utilization with respect to PUs as β when the SUs keep silent in the multichannel non-time-slotted CRNs. Let $\delta(t)$ be the random number of the idle sub-channels at the t-th time-slot. Since the PUs randomly use the licensed sub-channels, we can assume that all L licensed sub-channels have the same channel utilization with respect to the PUs, i.e.,

$$\beta_i = \beta, \qquad \text{for } 1 \leq i \leq L, \tag{12}$$

where β_i is the channel utilization for each licensed sub-channel with respect to the PUs. Then, we are able to derive the probability that u sub-channels can be used for SUs at the t-th time-slot as follows:

$$\Pr\{\delta(t) = u\} = \binom{L}{u} \beta^{L-u} (1-\beta)^u. \tag{13}$$

Based on the above probability, we can obtain the average number of channels that the SUs can utilize as follows:

$$\widetilde{L} = \sum_{u=0}^{L} u \Pr\{\delta(t) = u\}. \tag{14}$$

With the wireless FD-SS scheme, the PU's reactivation can be sensed by the SU during the entire SU's time-slotted frame. Denoting by I_f the average channel utilization of the PU when taking into account the impact of SUs on the PUs' reactivation, we have

$$I_f = \frac{VT_{sp}}{T_{tp}} = 1, \tag{15}$$

where V is the number of sensing periods in one time-slotted frame of the SU and T_{sp} is the time duration of one sensing period of the SU. The numerator (VT_{sp}) and the denominator T_{tp} of Eq. (15) denote the length of the sensing period in one frame and the length of one entire frame, respectively. Eq. (15) clearly shows that the SU can sense the sub-channels during the entire frame.

Then, we can obtain the average achieved throughput for PUs, denoted by T_{pu}, in multichannel saturated non-time-slotted CRNs where the SUs employ the wireless FDC-MAC protocol, as follows:

$$T_{pu} = LR\beta p_d(\epsilon, U, a, \kappa) I_f = LR\beta p_d(\epsilon, U, a, \kappa), \tag{16}$$

where R is the transmission rate of the licensed sub-channel.[2]

Next, we consider the average achieved throughput for SUs in multichannel saturated non-time-slotted CRNs. Without the PU's reactivation, we can derive the time spent by a successful transmission and the time spent by an unsuccessful transmission for the SU, denoted by T_s and T_c, respectively, as follows:

$$\begin{cases} T_s = RTS + SIFS + CTS + SIFS + T_d \\ \qquad\qquad + ACK + SIFS + DIFS; \\ T_c = RTS + DIFS, \end{cases} \tag{17}$$

where T_d is the time duration for the transmission of one data packet of the SUs, RTS is the length of a RTS frame, CTS is the length of a clear-to-send (CTS) frame, $SIFS$ is the time interval of short inter-frame space (SIFS), ACK is the length of an acknowledgement (ACK) frame, and $DIFS$ is the time interval of distributed coordination function inter-frame space (DIFS).

We can also derive the probability that an SU successfully transmits an RTS packet, the probability that the sub-channel is idle, and the probability that the collision occurs, denoted by P_s, P_i, and P_c, respectively, as follows:

$$\begin{cases} P_s = Mp(1-p)^{M-1}; \\ P_i = (1-p)^M; \\ P_c = 1 - Mp(1-p)^{M-1} - (1-p)^M. \end{cases} \tag{18}$$

Then, we can calculate the average time used for a successful transmission of the SU without the reactivation of the PU, denoted by $T(p, M)$, as follows:

$$T(p, M) = \frac{T_s P_s + T_c P_c + T_{ms} P_i}{P_s}, \tag{19}$$

where T_{ms} is the length of a mini-slot.

When the PU reactivates to use the licensed sub-channel, the SU will stop its transmission and try to find another idle

[2] Without loss of generality, we assume that each licensed channel has the same transmission rate R.

sub-channel to go on its transmission. This will generate new contentions for the SU. After the SU sensed the PU's reactivation, we derive the time spent by a successful transmission and the time spent by an unsuccessful transmission for another new contention, denoted by T_{sr} and T_{cr}, respectively, as follows:

$$\begin{cases} T_{sr} = RTS + SIFS + CTS + SIFS; \\ T_{cr} = RTS + DIFS. \end{cases} \tag{20}$$

Then, we can calculate the average time used for a successful transmission of the SU with the reactivation of the PU, denoted by $T_r(p, M)$, as follows:

$$T_r(p, M) = \frac{T_{sr}P_s + T_{cr}P_c + T_{ms}P_i}{P_s}. \tag{21}$$

Therefore, we can obtain the achieved throughput for SUs, denoted by T_{su}, under the saturation network case with the reactivation of the PUs, as follows:

$$T_{su} = \frac{\widetilde{L}RT_d\left[1 - p_f(\epsilon, U, d, \kappa)\right]}{T_s + \overline{T}_r}, \tag{22}$$

where

$$\overline{T}_r = \sum_{g=0}^{\infty} \left[\beta p_d(\epsilon, U, a, \kappa)\right]^g (1-\beta)\left[1 - p_f(\epsilon, U, d, \kappa)\right] \times \left[(g+1)T_{sp} + T_r(p, M)\right] \tag{23}$$

is the average time consumed for the SU to sense and contend another idle channel when the PU reactivated and occupied the licensed channel. The expression of $\overline{T}_r$, specified in Eq. (23), is the sum of the consumed time for the SU when the SU sensed the idle sub-channel with $(g+1)$ sensing periods and successfully contended this idle sub-channel. During the time $\overline{T}_r$, the SU can successfully find another idle sub-channel to go on its transmission. Therefore, the cost of $\overline{T}_r$ guarantees not only the timely reactivation of the PU, but also the successful transmission of the SU.

C. Throughput Analyses of Wireless FDC-MAC Protocol for Non-Saturation Network Case

In this section, we analyze the non-saturation network case, where the SUs may have the empty queues. Without loss of generality, we assume that the arrival of the SUs' packets follow the Poisson process, where we denote the mean arrival rate by λ.

For the non-saturation case, the average number of sub-channels, denoted by $\widetilde{L}_N$, which the secondary users can utilize is determined by:

$$\widetilde{L}_N = \min\{\lambda, \widetilde{L}\}. \tag{24}$$

where $\widetilde{L}$ is given by Eq. (14).

Then, we can obtain the average achieved throughput, denoted by $\widetilde{T}_{pu}$, for PUs in multichannel non-saturated non-time-slotted CRNs, where the SUs use the wireless FDC-MAC protocol, as follows:

$$\begin{aligned} \widetilde{T}_{pu} &= LR\beta\left[\frac{\widetilde{L} - \widetilde{L}_N}{\widetilde{L}} + p_d(\epsilon, U, a, \kappa)\frac{\widetilde{L}_N}{\widetilde{L}}\right] I_f \\ &= LR\beta\left[1 - (1 - p_d(\epsilon, U, a, \kappa))\frac{\widetilde{L}_N}{\widetilde{L}}\right], \end{aligned} \tag{25}$$

where β and I_f are characterized by Eqs. (12) and (15).

We can also derive the achieved throughput for SUs in multichannel non-saturated non-time-slotted CRNs, denoted by $\widetilde{T}_{su}$, as follows:

$$\widetilde{T}_{su} = \frac{T_{su}\widetilde{L}_N}{\widetilde{L}}, \tag{26}$$

where $\widetilde{L}$, T_{su}, and $\widetilde{L}_N$ are given by Eqs. (14), (22), and (24), respectively.

D. The Wireless ACK-Based Full-Duplex Cognitive MAC Protocol

We compare our proposed RTS/CTS-based FDC-MAC protocol with the benchmark scheme: the ACK-based FDC-MAC protocol. In the ACK-based FDC-MAC protocol, instead of using RTS/CTS-mechanism, the SUs employ the traditional ACK-mechanism to contend for the licensed channel [11]. If the SUs use the ACK-based FDC-MAC protocol, the contention among the SUs is more intensive than that of using our proposed RTS/CTS-based scheme. This can be seen when comparing the throughputs of using our developed RTS/CTS-based FDC-MAC protocol with the throughputs of using the ACK-based FDC-MAC protocol. Instead of repeating the similar derivations and analytical equations for ACK-based FDC-MAC protocol analysis, we just make the comparison between the throughputs of the RTS/CTS-based FDC-MAC protocol and the ACK-based FDC-MAC protocol by only using the numerical results in Section V.

E. The Wireless Half-Duplex Cognitive MAC Protocol

To show the advantage of using the wireless FDC-MAC protocol for multichannel non-time-slotted CRNs, in this section, we discuss that using the wireless half-duplex cognitive MAC (HDC-MAC) protocol for multichannel non-time-slotted CRNs [9]. The wireless HDC-MAC protocol is based on the wireless half-duplex energy detection spectrum sensing (HD-SS) scheme [6] and cannot solve the reactivation-failure problem in multichannel non-time-slotted CRNs.

With the wireless HDC-MAC protocol and the wireless HD-SS scheme, the PU's reactivation can only be sensed by the SU during one short sensing period in one SU's time-slotted frame. Denoting by I_h the average channel utilization of the PU when taking into account the impact of SUs on the PUs' reactivation, we have

$$I_h = \frac{T_{sp}}{T_{sp} + (V-1)T_{sp}} = \frac{1}{V}. \tag{27}$$

For the saturation network case, we can obtain the average achieved throughput, denoted by S_{pu}, for PUs in multichannel non-time-slotted CRNs where the SUs use the wireless HDC-MAC protocol as follows:

$$S_{pu} = LR\beta p_d(\epsilon, U, a, \kappa) I_h = \frac{LR\beta p_d(\epsilon, U, a, \kappa)}{V}. \tag{28}$$

Since with the wireless HD-SS scheme the SUs can only sense the reactivation of PUs during one short sensing period, the achieved throughput of PUs using the wireless HDC-MAC protocol will be largely lower than the achieved throughput of PUs using the wireless FDC-MAC protocol.

We can also derive the achieved throughput, denoted by S_{su}, for SUs under the wireless HDC-MAC protocol in saturated non-time-slotted CRNs as follows:

$$S_{su} = \frac{\widetilde{L} R T_d \left[1 - p_f(\epsilon, U, d, \kappa)\right]}{T_s}. \tag{29}$$

In the similar way, for the non-saturation network case, we can obtain the average achieved throughput, denoted by $\widetilde{S}_{pu}$, for PUs in multichannel non-time-slotted CRNs, where the SUs use the wireless HDC-MAC protocol, as follows:

$$\begin{aligned} \widetilde{S}_{pu} &= LR\beta \left[\frac{\widetilde{L} - \widetilde{L}_N}{\widetilde{L}} + p_d(\epsilon, U, a, \kappa) \frac{\widetilde{L}_N}{\widetilde{L}}\right] I_h \\ &= \frac{LR\beta \left[1 - \left(1 - p_d(\epsilon, U, a, \kappa)\right) \frac{\widetilde{L}_N}{\widetilde{L}}\right]}{V}. \end{aligned} \tag{30}$$

The achieved throughput, denoted by $\widetilde{S}_{su}$, for SUs with the wireless HDC-MAC protocol can be derived as follows:

$$\widetilde{S}_{su} = \frac{S_{su} \widetilde{L}_N}{\widetilde{L}}. \tag{31}$$

V. Performance Evaluations

In this section, we evaluate the wireless FD-SS based FDC-MAC protocol for multichannel non-time-slotted CRNs with numerical results. First, we compare the probabilities of false alarm and detecting a PU corresponding to non-time-slotted CRNs with the probabilities of false alarm and detecting a PU corresponding to time-slotted CRNs. Second, we show the impact of residual self-interference on the wireless FD-SS scheme. Third, we evaluate the throughput of PUs and SUs with the wireless FDC-MAC protocol in multichannel non-time-slotted CRNs. The main parameters for our proposed wireless FDC-MAC protocol are summarized in Table I, which have been popularly used in [6], [10], [11]. The probability of false alarm and the probability of detecting a PU are briefly written as p_f and p_d, respectively.

To reveal the impact of asynchronization on the probability of false alarm and the probability of detecting a PU, we compare the probabilities of false alarm and detecting a PU corresponding to non-time-slotted CRNs with the probabilities of false alarm and detecting a PU corresponding to time-slotted CRNs in Figs. 5 and 6. Fig. 5 compares the probability of false alarm corresponding to non-time-slotted CRNs with the probability of false alarm corresponding to time-slotted CRNs. For the non-time-slotted CRNs, we consider two scenarios: 1). $d = 500$, $M = 1500$, and $\kappa = 1$; 2). $d = 1000$, $M = 1500$, and $\kappa = 1$. As shown in Fig. 5, the asynchronization between the PUs and the SUs results that the probability of false alarm corresponding to non-time-slotted CRNs is higher than the probability of false alarm corresponding to time-slotted CRNs. The probability of false alarm increases as d increases corresponding to non-time-slotted CRNs. Fig. 6 compares the probability of detection corresponding to non-time-slotted CRNs with the probability of detection corresponding to time-slotted CRNs. For the non-time-slotted CRNs, we consider two scenarios: 1). $a = 500$, $M = 1500$, and $\kappa = 1$; 2). $a = 1000$, $M = 1500$, and $\kappa = 1$. As illustrated in Fig. 6, the asynchronization between the PUs and the SUs results that the probability of detection corresponding to non-time-slotted CRNs is lower than the probability of detection corresponding to time-slotted CRNs. The probability of detection decreases as a increases in non-time-slotted CRNs.

TABLE I
The Main Parameters for Our Proposed Wireless FDC-MAC Protocol

Parameter	Value	Description
RTS	288 bits	The length of RTS packet
CTS	240 bits	The length of CTS packet
ACK	240 bits	The length of ACK packet
R	1Mbit/s	Data rate of one licensed sub-channel
T_d	8184 μs	The time duration of one packet for SUs
T_{ms}	9 μs	Mini-slot interval
$SIFS$	28 μs	The time interval of short inter-frame space
$DIFS$	128 μs	The time interval of DIFS
T_{sp}	1 ms	The length of a sensing period
L	10	The number of sub-channels
V	10	The NO. of sensing periods of one SUs' frame
N	10	The number of PUs
M	10	The number of SUs
p	0.01	The probability of sending a packet

Since existing self-interference mitigation techniques cannot totally cancel the self-interference of the wireless full-duplex communications, we need to evaluate the impact of residual self-interference on the wireless FD-SS scheme. Figs. 7 and 8 show the impact of residual self-interference on the probability of false alarm and the probability of detecting a PU, respectively. The impact of the residual self-interference is characterized by the self-interference mitigation coefficient κ. As illustrated in Fig. 7, although the residual self-interference slightly decreases the probability of false alarm as compared with the probability of false alarm corresponding to the case that the self-interference is totally canceled $(\kappa = 1)$, the probability of false alarm corresponding to $\kappa = 0.9$ is very close to the probability of false alarm corresponding to $\kappa = 1$. Furthermore, the distance between the probability of false alarm corresponding to $\kappa = 0.9$ and the probability of false alarm corresponding to $\kappa = 1$ decreases as d decreases. As shown in Fig. 8, although the residual self-interference slightly decreases the probability of detection as compared with the probability of detection corresponding to the case that the self-interference is totally canceled $(\kappa = 1)$, the probability of detection corresponding to $\kappa = 0.9$ is very close to the probability of detection

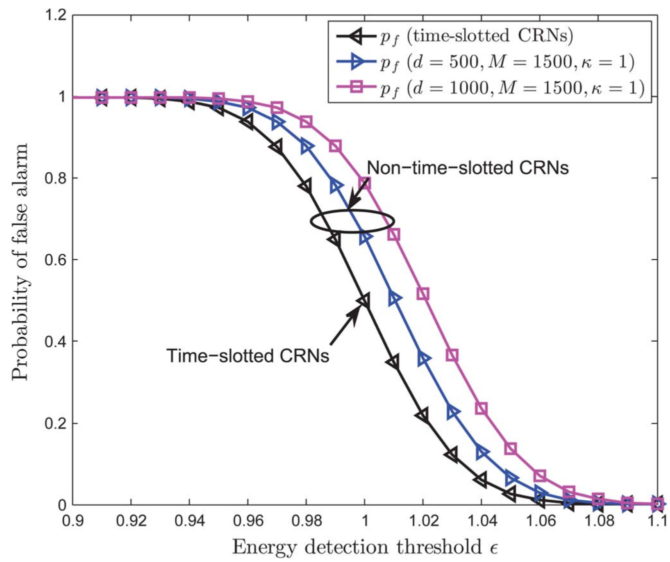

Fig. 5. The probability of false alarm in time-slotted CRNs and non-time-slotted CRNs.

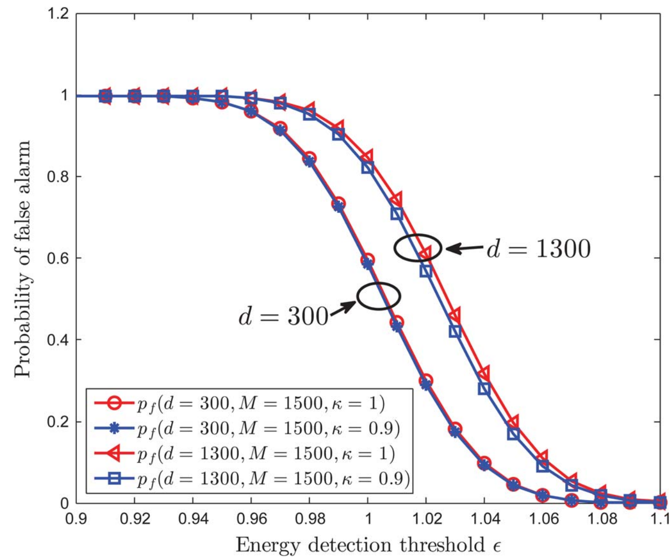

Fig. 7. The impact of self-interference on the probability of false alarm in non-time-slotted CRNs.

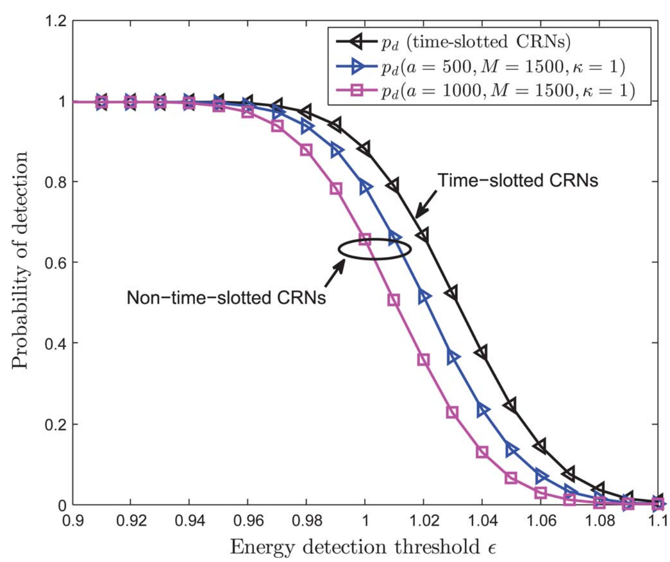

Fig. 6. The probability of detection in time-slotted CRNs and non-time-slotted CRNs.

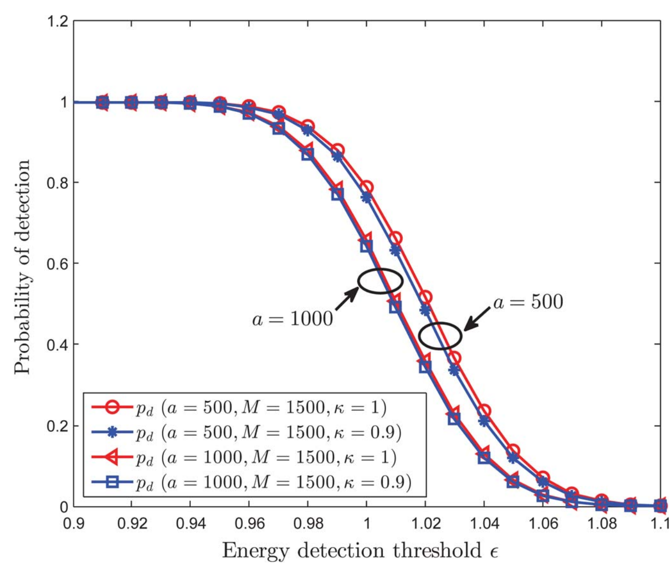

Fig. 8. The impact of self-interference on the probability of detection in non-time-slotted CRNs.

corresponding to $\kappa = 1$. Also, the distance between the probability of detection corresponding to $\kappa = 0.9$ and the probability of detection corresponding to $\kappa = 1$ increases as a decreases. Therefore, from Figs. 7 and 8, we can obtain that the residual self-interference causes little impact on the performance of the non-time-slotted CRNs. In the case corresponding to small d and large a, the impact of residual self-interference on non-time-slotted CRNs can be ignored.

Figs. 9 and 10 illustrate the achieved throughput of PUs with our proposed RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the wireless HDC-MAC protocol under saturation case and non-saturation case, respectively, in multichannel non-time-slotted CRNs, where the energy detection threshold ϵ is chosen to guarantee that the probability of detection is fixed to 0.9. The throughput of PUs without SUs in the wireless network is also plotted for comparison. As we can observe from Figs. 9 and 10, with our proposed RTS/CTS-based FDC-MAC protocol, the achievable throughput of PUs can be guaranteed to 90% of the throughput of PUs without SUs in the wireless network. However, under the same parameters settings, the achievable throughput using the ACK-based FDC-MAC protocol is significantly reduced to around only 55% of the throughput implemented by our proposed RTS/CTS-based FDC-MAC protocol. With the wireless HDC-MAC protocol, the achievable throughput of PUs is further decreased near to 11%. With the wireless HDC-MAC protocol, the obtained throughput of PUs cannot be guaranteed by controlling the probability of detection. Therefore, our developed wireless FDC-MAC protocol greatly outperforms both the ACK-based FDC-MAC protocol and the wireless HDC-MAC protocol for

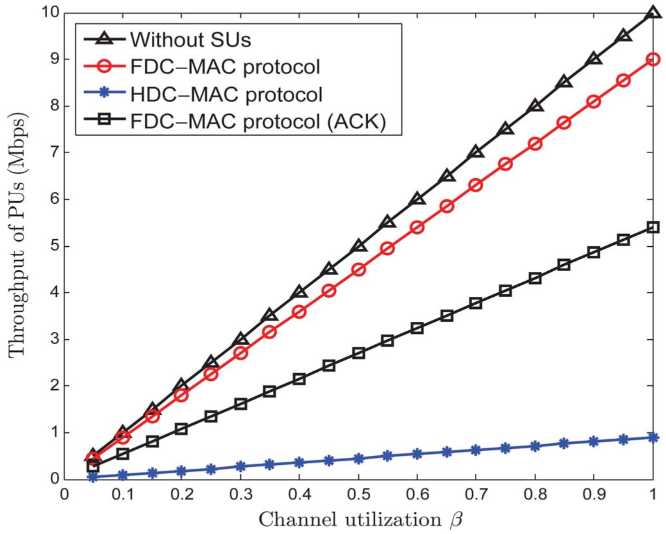

Fig. 9. The achieved throughput of PUs under the RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the HDC-MAC protocol in multichannel saturated non-time-slotted CRNs.

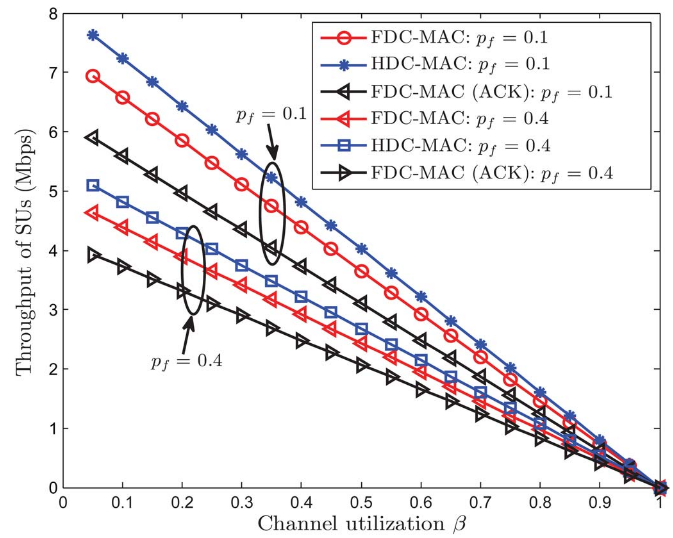

Fig. 11. The achieved throughput of SUs under the RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the HDC-MAC protocol in multichannel non-time-slotted CRNs.

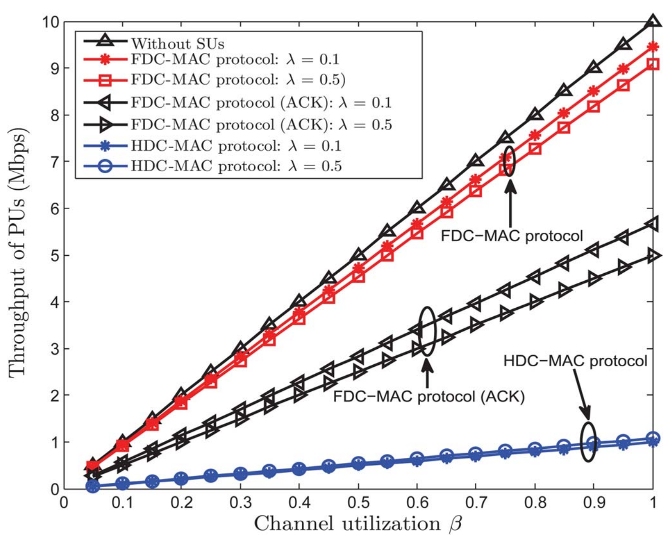

Fig. 10. The achieved throughput of PUs under the RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the HDC-MAC protocol in multichannel non-saturated non-time-slotted CRNs.

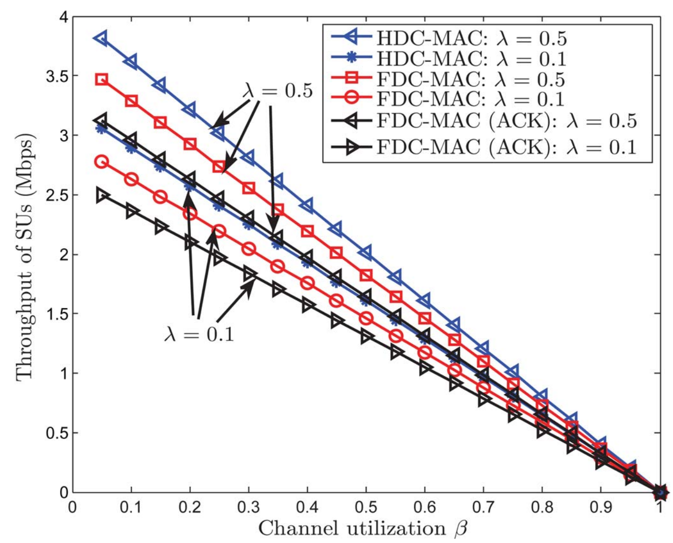

Fig. 12. The achieved throughput of SUs under the RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the HDC-MAC protocol in multichannel non-saturated non-time-slotted CRNs $(p_f = 0.1)$.

PUs in multichannel non-time-slotted CRNs. Comparing Fig. 9 with Fig. 10, we can observe that the achievable throughputs for PUs corresponding to the non-saturation network cases are closer to those of PUs without SUs in the wireless network as compared with the achieved throughputs of PUs corresponding to the saturation network cases.

Figs. 11 and 12 depict the achieved throughput of SUs with our proposed RTS/CTS-based FDC-MAC protocol, the ACK-based FDC-MAC protocol, and the wireless HDC-MAC protocols under saturation network case and non-saturation network case, respectively, in multichannel non-time-slotted CRNs, where the probability of false alarm is controlled by the energy detection threshold ϵ. As illustrated in Figs. 11 and 12, the achieved throughput of SUs with our proposed RTS/CTS-based FDC-MAC protocol is much larger than the achieved throughput of SUs with the ACK-based FDC-MAC protocol. Also, the achieved throughput of SUs with our proposed RTS/CTS-based FDC-MAC protocol is just slightly lower than the achieved throughput for SUs with the wireless HDC-MAC protocol, which is however significantly compensated by the very high throughput gain for PUs, as shown in Figs. 9 and 10. This slightly throughput drop of SUs is because the SUs need to spend extra contention time to effectively tackle the reactivation-failure problem in multichannel non-time-slotted CRNs. On the other hand, since the throughput of SUs with the wireless HDC-MAC protocol is obtained by significantly sacrificing the achievable throughput for PUs, it is not worth for the SUs with the wireless HDC-MAC protocol to achieve large throughput in multichannel non-time-slotted CRNs. In contrast, with our wireless FDC-MAC protocol, regardless whether the probability of false alarm is small ($p_f = 0.1$) or large ($p_f = 0.4$), the SUs can just slightly sacrifice achieved throughput to exchange for the high throughput gain in PUs which is verified by Figs. 9 and 11. From Fig. 12, we can observe that the achievable throughputs for SUs under the wireless FDC-MAC protocol are also just slightly lower than that for SUs under the wireless HDC-MAC protocol in the non-saturation network cases for the same reason.

VI. Conclusions

We proposed the framework for multichannel non-time-slotted CRNs, where the PUs randomly access and leave the licensed channel. Because of the asynchronization between primary and secondary networks, the synchronization between PUs and SUs cannot be guaranteed, which results in the reactivation-failure problem in multichannel non-time-slotted CRNs. To guarantee the transmission of PUs, we developed the wireless full-duplex spectrum sensing scheme for multichannel non-time-slotted CRNs. With the wireless full-duplex spectrum sensing scheme, the SUs can efficiently sense the sub-channels when the SUs are transmitting their signals using the sub-channels simultaneously. Based on our developed wireless full-duplex spectrum sensing scheme, we further developed the wireless full-duplex cognitive MAC protocol which efficiently solved the reactivation-failure problem in multichannel non-time-slotted CRNs. The obtained numerical results show that with the wireless full-duplex spectrum sensing scheme and the wireless full-duplex cognitive MAC protocol, the SUs can slightly sacrifice achieved throughput to exchange the high-throughput provisioning for PUs, which cannot be obtained by the wireless half-duplex cognitive MAC protocol for multichannel non-time-slotted CRNs.

References

[1] M. Mchenry, "Spectrum white space measurements," in *New America Foundation Broadband Forum*, Jun. 2003.
[2] J. Mitola, III, "Cognitive radio: An integrated agent architecture for software defined radio," Ph.D. dissertation, KTH Royal Inst. Technol., Stockholm, Sweden, 2000.
[3] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
[4] A. Goldsmith, S. A. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," *Proc. IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.
[5] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in *ad hoc* networks: A POMDP framework," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 589–600, Apr. 2007.
[6] Y. Liang, Y. Zeng, E. C. Y. Peh, and A. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008.
[7] W. Y. Lee and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3845–3857, Oct. 2008.
[8] 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.
[9] X. Zhang and H. Su, "CREAM-MAC: Cognitive radio-enabled multi-channel MAC protocol over dynamic spectrum access networks," *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 110–123, Feb. 2011.
[10] *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 22: Cognitive Wireless Ran Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE Std. 802.22-2011, 2011, 1–680.
[11] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
[12] D. Cabric, S. Mishra, and R. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Proc. 38th Asilomar Conf. Signals, Syst., Comput.*, Nov. 2004, pp. 772–776.
[13] Z. Quan, W. Zhang, S. J. Shellhammer, and A. H. Sayed, "Optimal spectral feature detection for spectrum sensing at very low SNR," *IEEE Trans. Commun.*, vol. 59, no. 1, pp. 201–212, Jan. 2011.
[14] R. Bozidar *et al.*, "Rethinking indoor wireless mesh design: Low power, low frequency, full-duplex," in *Proc. 5th IEEE WIMESH*, Jun. 2010, pp. 1–6.
[15] S. Gollakota and D. Katabi, "Zigzag decoding: Combating hidden terminals in wireless networks," in *Proc. ACM SIGCOMM Conf. Data Commun.*, New York, NY, USA, 2008, pp. 159–170.
[16] J. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. 16th ACM MOBICOM*, Chicago, IL, USA, Sep. 2010, pp. 1–12.
[17] M. Jain *et al.*, "Practival, real-time, full duplex wireless," in *Proc. 17th ACM MOBICOM*, Las Vegas, NV, USA, Sep. 2011, pp. 301–312.
[18] E. Everett, M. Duarte, C. Dick, and A. Sabharwal, "Empowering full-duplex wireless communication by exploiting directional diversity," in *Proc. 45th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2011, pp. 2002–2006.
[19] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.
[20] D. Senaratne and C. Tellambura, "Beamforming for space division duplexing," in *Proc. IEEE ICC*, Jun. 2011, pp. 1–5.
[21] W. Cheng, X. Zhang, and H. Zhang, "Optimal dynamic power control for full-duplex bidirectional-channel based wireless networks," in *Proc. IEEE INFOCOM*, 2013, pp. 3120–3128.
[22] W. Cheng, X. Zhang, and H. Zhang, "Full duplex spectrum sensing in non-time-slotted cognitive radio networks," in *Proc. IEEE MILCOM*, 2011, pp. 1029–1034.

Wenchi Cheng received his B.S. and Ph.D. degrees in telecommunication engineering from Xidian University, China, in 2008 and 2014, respectively. He has been an Assistant Professor the Department of Telecommunication Engineering, Xidian University, since 2013. From 2010 to 2011, he worked as a visiting Ph.D. student under the supervision of Professor Xi Zhang at the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Dwight Look College of Engineering, Texas A&M University, College Station, TX, USA.

His research interests focus on 5G wireless networks, wireless full-duplex transmission, statistical QoS provisioning, cognitive radio techniques, and energy-efficient wireless networks. He has published multiple papers in IEEE Journal on Selected Areas in Communications, IEEE INFOCOM, IEEE GLOBECOM, IEEE ICC, and so on. He is serving as a Technical Program Committee members for IEEE INFOCOM 2016 and for the IEEE ICC 2015.

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, USA, 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, MI, USA.

He is currently a 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 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, Australia. He was with the Networks and Distributed Systems Research Department, AT&T Bell Laboratories, Murray Hill, New Jersey, and AT&T Laboratories Research, Florham Park, New Jersey, in 1997. He has published more than 300 research papers on wireless networks and communications systems, network protocol design and modeling, statistical communications, random signal processing, information theory, and control theory and systems. He 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 is an IEEE Distinguished Lecturer of both IEEE Communications Society and IEEE Vehicular Technology Society. He received Best Paper Awards at IEEE GLOBECOM 2014, IEEE GLOBECOM 2009, IEEE GLOBECOM 2007, and IEEE WCNC 2010, respectively. He also received a 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.

Prof. Zhang is serving or has served as an Editor for IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, and IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, twice as a Guest Editor for IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS for two special issues on "Broadband Wireless Communications for High Speed Vehicles" and "Wireless Video Transmissions," an Associate Editor for IEEE COMMUNICATIONS LETTERS, twice as the Lead Guest Editor for IEEE COMMUNICATIONS MAGAZINE for two special issues on "Advances in Cooperative Wireless Networking" and "Underwater Wireless Communications and Networks: Theory and Applications," and a Guest Editor for IEEE WIRELESS COMMUNICATIONS for special issue on "Next Generation CDMA vs. OFDMA for 4G Wireless Applications," an Editor for Wiley's JOURNAL ON WIRELESS COMMUNICATIONS AND MOBILE COMPUTING, JOURNAL OF COMPUTER SYSTEMS, NETWORKING, AND COMMUNICATIONS, and Wiley's JOURNAL ON SECURITY AND COMMUNICATIONS NETWORKS, and an Area Editor for Elsevier's JOURNAL ON COMPUTER COMMUNICATIONS, among many others. He is serving or has served as the TPC Chair for IEEE GLOBECOM 2011, TPC Vice-Chair IEEE INFOCOM 2010, TPC Area Chair for IEEE INFOCOM 2012, Panel/Demo/Poster Chair for ACM MobiCom 2011, General Vice-Chair for IEEE WCNC 2013, Panel/Demo/Poster Chair for ACM MobiCom 2011, and TPC/General Chair for numerous other IEEE/ACM conferences, symposia, and workshops.

Hailin Zhang (M'98) received the B.S. and M.S. degrees from Northwestern Polytechnic University, Xi'an, China, in 1985 and 1988, respectively, and the Ph.D. degree from Xidian University, Xi'an, China, in 1991. In 1991, he joined the School of Telecommunications Engineering, Xidian University, where he is a Senior Professor, the Dean, and the Director of the Key Laboratory in Wireless Communications sponsored by the China Ministry of Information Technology, a key Member of the State Key Laboratory of Integrated Services Networks, one of the state government specially compensated scientists and engineers, and a field leader in telecommunications and information systems. He is also an Associate Director for the National 111 Project. He is the author or coauthor of more than 100 papers in journals and conferences. His current research interests include key transmission technologies and standards on broadband wireless communications for 5 G wireless access systems.