Opportunistic MAC Protocols for Cognitive Radio Based Wireless Networks

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***Abstract*— Recently, cognitive radio technology has attracted more and more attention since it is a novel and effective approach to improve the utilization of the precious radio spectrum. We propose MAC protocols for the cognitive radio based wireless networks. Specifically, the cognitive MAC protocols allow secondary users to identify and use the available frequency spectrum in a way that constrains the level of interference to the primary users. In our schemes, each secondary user is equipped with two transceivers. One of the transceivers is tuned to a dedicated control channel, while the other is used as a cognitive radio that can periodically sense and dynamically use an identified available channels. Our proposed schemes integrate the spectrum sensing at the PHY layer and packet scheduling at the MAC layer. Our schemes smoothly coordinate the two transceivers of the secondary users to enable them to collaboratively sense and dynamically utilize the available frequency spectrum.**

***Index Terms*— Cognitive radio, multi-channel MAC, opportunistic spectrum access.**

I. Introduction

THE RAPID growth in the ubiquitous wireless services have 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 pointed out that the static frequency allocation leads to 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 the unused spare spectrum opportunities exist.

In order to better utilize the licensed spectrum, the Federal Communication Committee (FCC) has recently suggested a new concept of dynamic spectrum allocation [2]. Correspondingly, cognitive radio technology is proposed to take advantage of the more open spectrum policy. Cognitive radio is typically built on the software-defined radio (SDR) technology, in which the transmitter's operating parameters, such as frequency range, modulation type, and maximum transmission power can be altered by software [4]. In the cognitive radio networks, the *secondary* (unlicensed) users can periodically search and identify available channels in the spectrum. Based on the scanned results, the secondary users dynamically tune its transceivers to the identified available channel to communicate among themselves without disturbing the communications of the *primary* (licensed) users.

Although its basic idea is simple, the cognitive radio networks face new challenges that are not present in the conventional wired or wireless networks [3][6]. Specifically, the varying channel availability implies a few nontrivial problems to the medium access control (MAC) layer. One of the critically important design problems is how the secondary users decide when and which channel it should tune to in order to transmit/receive packets without affecting the communications of the primary users. To answer these questions, in this paper we propose the opportunistic MAC protocols for cognitive radio based wireless networks.

The rest of this paper is organized as follows. Section II presents the primary users' channel-usage model. Section III develops our opportunistic MAC protocols. Section IV derives the mathematical model to analyze the proposed protocol. Section V evaluates our protocol based on the analytical model. The paper concludes with Section VI.

II. Primary Users' Channel-Usage Model

We consider that a spectrum licensed to the primary users consists of n channels, in which the primary users communicate with each other based on a synchronous slot structure, as depicted in Fig. 1. We model each channel as an ON-OFF source alternating between state ON (active) and state OFF (inactive). An ON/OFF state models a time slot in which the primary user signals is or is not occupying a channel. The secondary users can utilize the OFF time slot to transmit their own signals. Suppose that each channel changes its state independently. Let λ_i be the probability that the ith channel transits from state ON to state OFF and μ_i be the probability that the ith channel transits from state OFF to state ON, where $1 \leq i \leq n$. Then, the channel state can be characterized by a Markov chain as shown in Fig. 2.

For the ith channel in time slot t, the state of the ith channel, denoted by $I_i(t)$, corresponds to a binary random value, i.e., 0 corresponds to idle and 1 to active. Hence, sensing a given channel produces a binary random sequence. The network state in time slot t can be characterized as $[I_1(t), I_2(t), \cdots, I_n(t)]$. Then, the ith channel utilization, denoted by z_i, with respect

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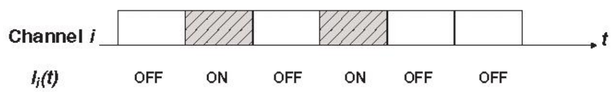

Fig. 1. The channel state for the ith channel.

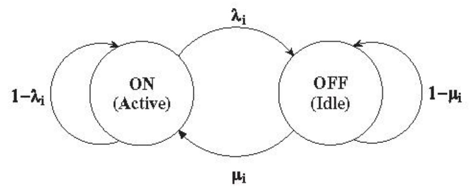

Fig. 2. The ON-OFF channel usage model for primary users.

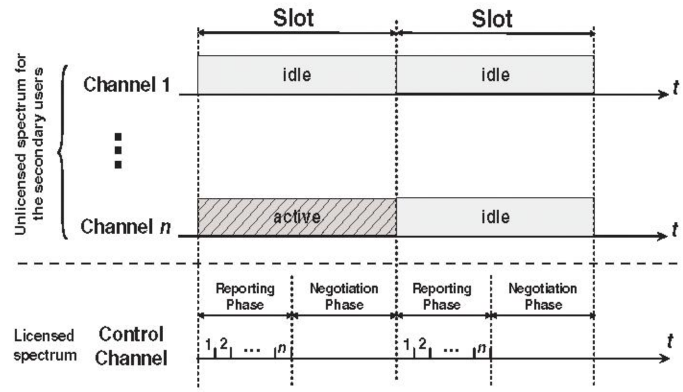

Fig. 3. The principle of our proposed MAC protocols.

to the primary users, can be written as:

$$z_i = \lim_{T \to \infty} \frac{\sum_{t=1}^{T} I_i(t)}{T} = \frac{\mu_i}{\lambda_i + \mu_i}, \quad (1)$$

where $1 \leq i \leq n$.

III. Our Proposed MAC Protocols

In our proposed schemes, each secondary user is equipped with two sets of transceivers. The first transceiver is devoted to operating over the dedicated control channel. The secondary users use the control transceivers to obtain the information of available licensed channels, and to negotiate with the others via contention-based algorithms (e.g., IEEE 802.11 and p-persistent Carrier Sense Multiple Access). The second transceiver consists of a SDR module such that it can tune to any n licensed channels to sense, receive, and transmit signals/packets. For convenience, we call the first transceiver control transceiver, and the second one SDR in the rest of our paper.

Figure 3 shows the principle of our proposed schemes. The control channel also consists of periodical time slots. The slots of the control channel have the same length as those of cognitive channels and the slots of both control channel and cognitive channels are synchronized. In the control channel, slot is divided into two phases, namely, reporting phase and negotiation phase. The reporting phase can be further divided into n sub-channels via time division. That implies that the reporting phase consists of n mini-slots.

Figure 4 lists the pseudo code for our proposed scheme. At the beginning of the time slot, the secondary users use SDR's to sense one of n channels, say ith Channel, $(1 \leq i \leq n)$. If the secondary user perceives that the CH-i channel is idle, then it uses the control transceiver to send a beacon during the ith mini-slot over the control channel. Otherwise, it does not sends any beacons. Each mini-slot lasts T_{ms}, which is set to be long enough to determine whether channel is busy or not.[1] Clearly, if each of the n channels is sensed by at least one secondary user, all the secondary users get the information about the activity of the whole licensed spectrum. If we denote

[1]Following the settings in IEEE 802.11a [7], we set T_{ms} to be equal to 9 μs in the rest of our paper.

Opportunistic MAC protocol: code for every secondary user

```
Initially: NAC := 0, LAC := ∅, Num_CTS := 0

  Reporting phase:
  For Control transceiver:
     Listens on the control channel
     Upon receiving a beacon at kth mini-slot
        NAC := NAC + 1 //Update the number of available channels
        LAC(NAC) := k //Update the list of available channels
     Upon Informed by SDR that jth channel is idle
        Send a beacon at jth mini-slot
        NAC := NAC + 1 //Update the number of available channels
        LAC(NAC) := k //Update the list of available channels
  For SDR:
     Senses channel j which is decided by the sensing policy.
     If channel j is idle
        Inform Control transceiver that jth channel is idle

  Negotiation phase:
  For Control transceiver:
     Upon receiving CTS
        Num_CTS := Num_CTS + 1
        If destination address is myself // negotiation is succeeded
           Set acc_prio := Num_CTS at the end of this phase
     If the outgoing queue is not empty
        Contend the channel to negotiate with the destination node
  For SDR:
     If the outgoing queue is not empty and acc_prio ≤ NAC
        Tune to channel LAC(acc_prio) to send data packet
```

Fig. 4. Pseudo code of the MAC protocol for the secondary users, where NAC is the number of known available channels, LAC is the list of known available channels, and Num_CTS is the number of CTS packets the node receives.

T_S, T_{RP}, and T_{NP} as the time duration of the slot, reporting phase, and negotiation phase, respectively, then we obtain:

$$T_S = T_{RP} + T_{NP} = nT_{ms} + T_{NP}. \quad (2)$$

To know 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. The authors of [5] developed a partially observable Markov decision processes (POMDPs) based channel-sensing policy. Although this policy can well exploit the available frequency spectrum, it is way complicated, especially for the networks consisting of nodes with constrained hardware resource (e.g., wireless sensor networks). Instead, we develop a simple but efficient sensing mechanism, namely random sensing policy in this paper. Our following analyses show that our proposed scheme can also

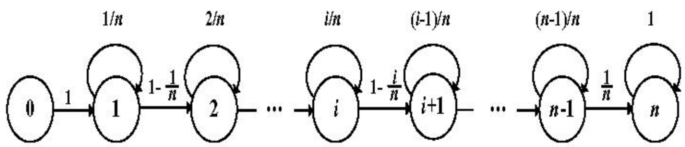

Fig. 5. The Markov chain for the number of sensed channels, where the variable in each circle represents the number of distinct channels sensed by the secondary users.

fully utilize the available frequency spectrum when the number of secondary users is much more than the number of channels, which is the typical case in the realistic applications.

In the random sensing policy, the secondary users cooperate to sense the licensed channels. Each secondary users chooses one of the n licensed with probability $1/n$ to sense. The chosen channels among the secondary users are independently identical distributed (i.i.d.). Consider that there are u secondary users in the networks. Each secondary user independently and uniformly chooses a channel. Let S be the total number of distinct channels that the secondary users can sense. Then, we use a Markov chain to calculate the probability mass function (pmf) of S, denoted by $\Pr\{S = s\}$, that the number of channels sensed by the secondary users is s. The probability that a given channel is sensed by a secondary node is $1/n$. Thus, we can depict the channel sensing process as a Markov chain as shown in Fig. 5, where the variable in the circle represents the number of channels sensed by the secondary users. Based on the Markov chain shown in Fig. 5, we can determine the transition matrix, denoted by $\mathbf{Q}$, as

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

Note that $\mathbf{Q}$ is an $(n+1) \times (n+1)$ upper bidiagonal matrix. The probability 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 state of 0-sensed-channel to state of s-sensed-channel. Therefore, $\Pr\{S = s\}$ can be expressed as

$$\Pr\{S = s\} = \mathbf{Q}^u|_{(0,s)}, \tag{3}$$

where $\mathbf{X}|_{(i,j)}$ denotes the element in position row i, column j of matrix $\mathbf{X}$.

By using Eq. (3), we obtain the inverse cumulative probability function (CDF) of S with different number of secondary users when $n = 10$ as shown in Fig. 6. In the random sensing policy, the more the secondary users are, the more licensed channels are sensed. When the secondary users are over three

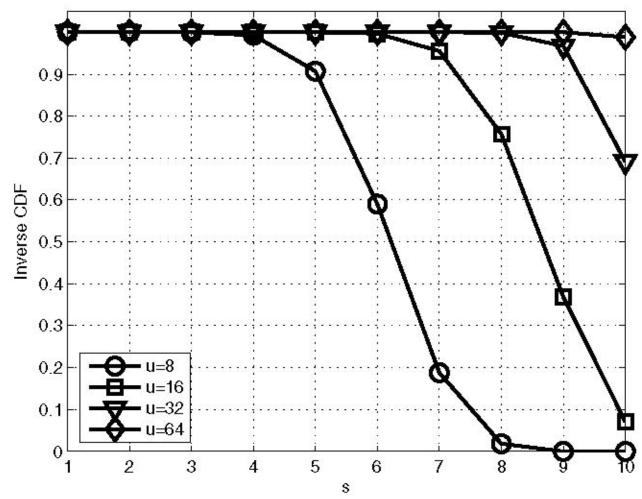

Fig. 6. The inverse cumulative probability function of the number of channels sensed by the secondary users (i.e., $\Pr\{S \geq s\}$) when $n = 10$.

times more than the licensed channels, the random sensing policy can ensure that almost all the licensed channels are sensed by secondary users. Note that in the realistic applications, the secondary users are much more than the licensed channels. The random sensing policy provisions the simple software and hardware implementations for the secondary users, while ensuring that almost all the licensed channels are sensed.

IV. The Analytical Model

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

A. The Number of Known Available Channels

Due to the unreliable wireless communications and limitations of the hardware, the secondary users may sense the channels incorrectly, and thus get the wrong information about the activity of the channels. Let p_c be the probability that the secondary users sense the channel correctly, and $M(t)$ be the random number of the actual available channels known by the secondary users at time slot t. Similar as the analyses in Section III, we can use a Markov chain to model the number of available channels known by the secondary users. Given $M(t) = m$ at time slot t, the conditional transition probabilities can be written as

$$\Pr\{w_{i,j}|M(t) = m\} = \begin{cases} 1 - p_c\left(\frac{m-i}{n}\right), & i = j, \\ p_c\left(\frac{m-i}{n}\right), & j = i+1, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

where $0 \leq m \leq n$ and $0 \leq i, j \leq m$. Given $M(t) = m$, the above transition probabilities constitute the transition matrix, denoted by $\mathbf{W}_m$, which is a $(m + 1) \times (m + 1)$ upper bidiagonal one. Let u be the number of secondary users.

The probability that the random number, denoted by $L(t)$, of available channels perceived by the secondary users is equal to i at time slot t can be given by:

$$\begin{aligned}&\Pr\{L(t)=i|M(t)=m\}\\&=\Pr\{\text{The number of available channels is } i\ |M(t)=m\ \}\\&=(\mathbf{W}_m)^u|_{(0,i)},\end{aligned} \tag{5}$$

where $0 \le i \le n$, and $\mathbf{X}|_{(i,j)}$ represents the element in position row i, column j of matrix $\mathbf{X}$. Suppose that all the channels have the same channel utilization, denoted by z, with respect to the primary users, i.e.,

$$z = z_i = z_j, \forall\ 1 \le i, j \le n \text{ and } i \ne j, \tag{6}$$

where z_i is determined by Eq. (1). Since the states among channels are independent and the probability that the channel is active is z, $M(t)$ is following the binomial distribution, that is,

$$\Pr\{M(t)=m\} = \binom{n}{m} z^{n-m}(1-z)^m. \tag{7}$$

By using Eqs. (5) and (7), the pmf for the number of known available channels can be expressed as

$$\begin{aligned}&\Pr\{L(t)=i\}\\&\quad=\textstyle\sum_{m=0}^{n}\Pr\{M(t)=m\}\Pr\{L(t)=i|M(t)=m\}\\&\quad=\textstyle\sum_{m=0}^{n}\binom{n}{m}z^{n-m}(1-z)^m[(\mathbf{W}_m)^u|_{(0,i)}]\end{aligned} \tag{8}$$

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

$$\overline{L} = \sum_{i=0}^{n} i \Pr\{L(t)=i\}. \tag{9}$$

B. The p-persistent CSMA for Negotiation Phase

Under the p-persistent CSMA protocol, if detecting busy channel, the node with non-empty queue waits till channel becomes idle, and then transmits the packet with probability p. Let v be the average number of the active secondary users which have non-empty queues. Under our proposed scheme, in the negotiation phase, on average v active secondary users nodes send RTS/CTS packets to contend for the available channel of next time slot. If we denote T_{ms}, T_{succ} and T_{coll} as the time of mini-slot, successful transmission, and failure transmission, respectively, then we have

$$\begin{cases} T_{\text{succ}} = RTS + SIFS + CTS + DIFS \\ T_{\text{coll}} = RTS + DIFS \end{cases} \tag{10}$$

In the p-persistent CSMA, the probability, denoted by P_{idle}, that the channel is idle is determined by

$$P_{\text{idle}} = (1-p)^v. \tag{11}$$

The probability, denoted by P_{succ}, that a node successful transmits a RTS frame can be obtained by

$$P_{\text{succ}} = vp(1-p)^{v-1}. \tag{12}$$

The probability, denoted by P_{coll}, that the collision occurs can be written as

$$P_{\text{coll}} = 1 - P_{\text{idle}} - P_{\text{succ}}. \tag{13}$$

The average time used for a successful transmission can be expressed as

$$T(p,v) = \frac{T_{ms}P_{\text{idle}} + T_{\text{succ}}P_{\text{succ}} + T_{\text{coll}}P_{\text{coll}}}{P_{\text{succ}}}. \tag{14}$$

If we let h be the maximum number of nodes that successfully receive CTS packets (i.e., the nodes that have the chance to exchange data in the next time slot), then h satisfies the following inequality

$$\sum_{i=0}^{h} T(p, v-i) \le T_{NP} = T_S - nT_{ms}, \tag{15}$$

where T_{NP} is the length of the negotiation phase.

C. The Aggregate Throughput

Under our proposed scheme, the number, denoted by C, of channels that will be used by the secondary users is less than the number of nodes that successfully receive the CTS packets in the previous negotiation phase, and is no more than the number of available channels detected by the secondary users, that is,

$$C(t) = \min\{h, L(t)\}, \tag{16}$$

where h is the number of secondary users that successfully contend for the opportunity of data transmission, and can be calculated by combining and applying Eqs. (10)-(15). Thus, the average number of channels that will be used by the secondary users

$$E[C(t)] = \begin{cases} \sum_{i=0}^{h} i\Pr\{L(t)=i\} + \\ \quad \sum_{i=h+1}^{n} h\Pr\{L(t)=i\}, & h < n, \\ \overline{L}, & h \ge n. \end{cases} \tag{17}$$

Then, we further study the asymptotical case in terms of the number of secondary users. As the number (u) of secondary users goes to infinite, based on Eq. (5) we get

$$\begin{aligned}\lim_{u\to\infty}\Pr\{L(t)=i|M(t)=m\} &= \lim_{u\to\infty}(\mathbf{W}_m)^u|_{(0,i)}\\ &= \begin{cases}1, & i=m,\\ 0, & i\ne m.\end{cases}\end{aligned} \tag{18}$$

This implies that when the number of secondary users becomes larger and larger, the system can achieve higher channel utilization. Thus, the asymptotical channel number occupied by the secondary users can be written as

$$\mathcal{C} = \lim_{u\to\infty} E[C(t)] = \min\{h, \overline{L}\}. \tag{19}$$

Let the data rate of ith licensed channel for the secondary users be R_i, where $0 \le i \le n$. Without loss of generality, we assume that all the n licensed channels have the same bandwidth, i.e., $R_i = R_j = R, \forall\ 0 \le i, j \le n$ and $i \ne j$. Since the transmission over the data channels are contention-free in

TABLE I

THE PARAMETERS FOR OUR PROPOSED SCHEME.

RTS	44 Bytes	The length of RTS packet
CTS	38 Bytes	The length of CTS packet
T_{ms}	9 μs	Mini-slot interval
SIFS	15 μs	Short interframe space
DIFS	34 μs	DCF interframe space
p	0.01	The prob. of sending a packet
R	1 Mbps	Data rate

our proposed protocols, the aggregate throughput, denoted by A, for the secondary users can be simply expressed as:

$$A = E[C(t)]R. \tag{20}$$

Then, by using Eqs. (19) and (20), we derive the limit of A, denoted by A', for the aggregate throughput of the secondary users as following:

$$A' = \lim_{u\to\infty} E[C(t)]R = \min\{h, \overline{L}\}R. \tag{21}$$

Since A given by Eq. (20) is a monotonically increasing function of u, A' represents the upper bound for the aggregate throughput of the secondary users.

V. PERFORMANCE EVALUATIONS

Based on the above discussions, we evaluate the performance of our proposed scheme in terms of aggregate throughput in this section. The parameters for our proposed algorithm are listed in Table I. We first investigate the impact of the duration for a time slot (T_S) on the aggregate throughput when the number of secondary users change from 8 to 64 with $p_c = 0.8$, $z = 0.1$, and $n = 5$. By using Eq. (20), we obtain the numerical results as shown in Fig. 7. On one hand, when the duration of time slot is less than 6.5 ms, the aggregate throughput is mainly determined by the number of nodes that successfully negotiate within the negotiation phase. For example, when $T_S = 4$ ms, there are 3 nodes which successfully receive CTS packets, resulting that the maximum aggregate throughput is no more than 3 Mbps regardless of the number of secondary users. The similar observation can be applied to the case of $T_S = 2$ ms. On the other hand, when $T_S \geq 6.5$ ms, $h = 6 > n = 5$, the aggregate throughput depends on $\overline{L}$, i.e., the number of available channels which are perceived by the secondary users.

To better study the random sensing policy of our proposed scheme, in the following scenarios, we focus on the case of large T_S such that $h \geq n$, that is, the number of secondary users that successfully contend for the opportunity of data transmission is no less than the number of data channels. In these scenarios, we set $T_S = 10$ ms. Thus, the aggregate throughput is only determined by the number of known available channels perceived by the secondary users.

First, given that the number of channels is 5 and the channel utilization by the primary users is 0.1, we obtain the numerical results of the aggregate throughput against p_c with different number of secondary users, which is shown in Fig. 8. The aggregate throughput gets larger as the probability that the secondary users sense the channels correctly increases. Under

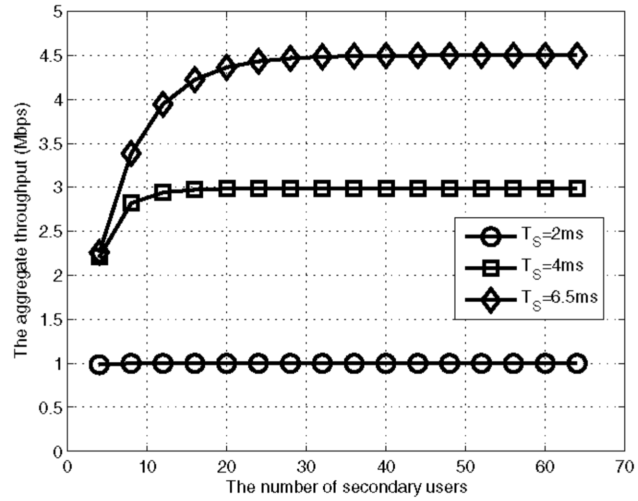

Fig. 7. The aggregate throughput versus the number of secondary users with different T_S's when $p_c = 0.8$, $z = 0.1$, and $n = 5$.

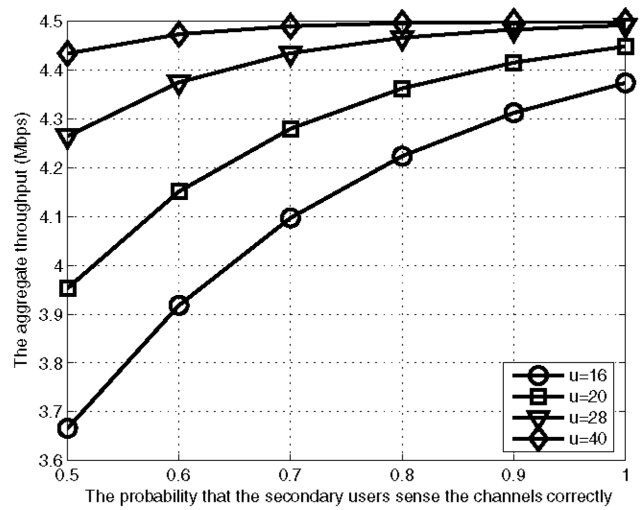

Fig. 8. The aggregate throughput against p_c with different number of secondary users when $n = 5$ and $z = 0.1$.

the same p_c, the more secondary users, the higher aggregate throughput, , because more secondary users implies more idle channels can be correctly sensed based on the random sensing policy of our proposed scheme. We also observe that the increase of p_c has less impact on the aggregate throughput when $u = 40$ than that when $u = 16$.

Second, Fig. 9 plots that the aggregate throughput against the number of secondary users with different number of licensed channels when $p_c = 0.8$ and $z = 0.2$. Clearly, under the same channel utilization (z) by the primary users, the more licensed channels, the more aggregate throughput for the secondary users. The dash lines in Fig. 9 represents the upper bounds (A') of the aggregate throughput for different n's, which is given by Eq. (21). As the increase of the number of licensed channels, the aggregate throughput approaches to the upper bound more slowly. For example, the aggregate

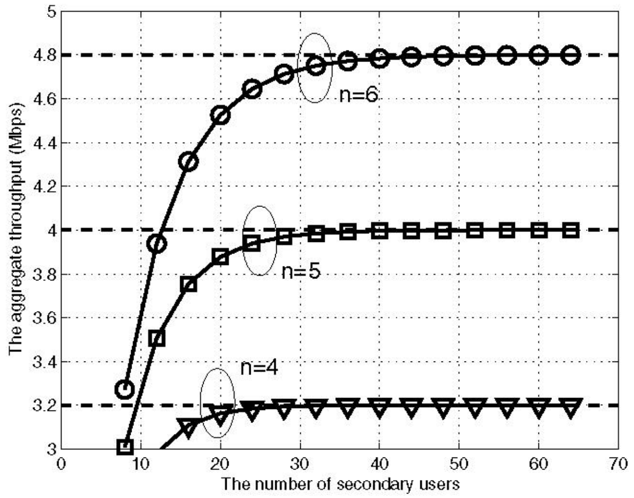

Fig. 9. The aggregate throughput against the number of secondary users with different number of licensed channels when $p_c = 0.8$ and $z = 0.2$. The dash lines represents the different upper bound of the aggregate throughput for different n's.

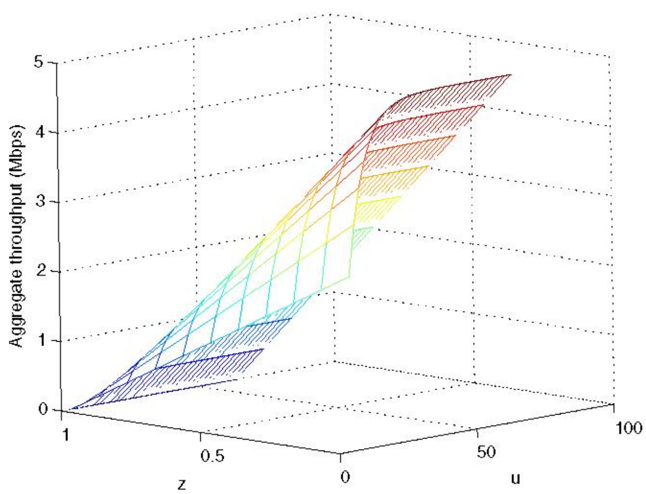

Fig. 10. The aggregate throughput versus u and z when $p_c = 0.8$ and $n = 5$.

throughputs reach the upper bounds when $u \geq 32, 40$, and 48 for $n = 4, 5$, and 6, respectively.

Finally, We plot the numerical results of the aggregate throughput, when u changes from 8 to 64, z varies from 0 to 1 in Fig. 10. If we fix the number of secondary users, the aggregate throughput of the secondary users increases nearly linearly with the channel utilization z of the primary users. This is expected because the lower channel utilization implies that the secondary users can use more available channels which are not occupied by the primary users.

VI. Conclusions

We propose the opportunistic MAC protocols for the cognitive radio based wireless networks. Specifically, the cognitive MAC protocols allow secondary users to identify and use the available frequency spectrum without imposing interference to the primary users. Under our proposed schemes, each secondary user is equipped with two transceivers, including a control transceiver and a SDR-based transceiver. In particular, the control transceivers is tuned to a dedicated control channel, while the SDR can tune to any available channels to sense, receive, and transmit signals/packets. Our proposed scheme can sense and dynamically utilize the available frequency spectrum by integrating the spectrum sensing at the PHY layer and packet scheduling at the MAC layer. In addition, we develop analytical models to evaluate the performance of our proposed scheme.

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