

Distributed Spectrum Sensing and Access with Secondary Channel Quality in Cognitive Radio Networks

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Abstract—We consider a cognitive radio network where many secondary users compete with each other for a primary spectrum. The design objective is to determine, in each frame, which secondary user (SU) transmits data when primary user (PU) is idle. We propose a sensing and access scheme which is adopted in a fully distributed manner. First we assume that there is no sensing error and compare the average throughput of the proposed scheme with that of optimum. The performance of the proposed scheme if there is no sensing error has a feature similar to optimal case. And the performance is improved in a large network with much more secondary users. Next we analyze the performance of the proposed scheme if there is sensing error. Under imperfect sensing, the average throughput of the proposed scheme shows a different feature. The numerical examples show that there exists the optimal number of SUs and sensing duration to maximize the average throughput for a given target detection probability.

Keywords—Cognitive radio networks, distributed spectrum sensing, channel quality

I. INTRODUCTION

Wireless communications rely on the frequency spectrum as a fundamental resource. With the increasing demand from upcoming wireless communication technologies, the available frequency spectrum became scarce. Many frequency bands, that are previously assigned, are almost unused, whereas some networks serve an enormous communication demand.

Cognitive radio technology is regarded as an efficient solution to mitigate the inflexibility of existing spectrum regulations [1]-[3]. In a cognitive radio network, the secondary users (SUs) have cognitive capabilities, such as sensing the spectrum reliably to check whether it is being used by a primary user. SUs opportunistically operate in the frequency bands originally allocated to the primary users (PUs) when the PUs are inactive. The model is known as opportunistic spectrum access (OSA) and is one of the approaches envisioned for dynamic spectrum management. OSA has been intensively studied in the literature [4]-[10].

It covers spectrum sensing and access mechanisms. And cognitive MAC design for OSA has been addressed under

different network architectures [9]. Recently sensing-based spectrum sharing is proposed for cognitive radio networks. In [4]-[6], they propose MAC frame structure supporting periodic spectrum sensing and study the problem to maximize the achievable throughput. They consider a system model where a SU senses and accesses a primary spectrum.

Spectrum access and sharing in a multiple secondary user environment has been studied in many literature. In [7], they characterize a tradeoff between sum throughput maximization and primary user interference minimization and identify the optimal amount of spectrum sharing that maximizes the total system throughput. They do not consider the way in that many secondary users efficiently sense and access spectrum. In [8], they propose a primary-prioritized Markov approach for dynamic spectrum access. The interactions between primary users and the secondary users are modelled as continuous-Markov chains. They optimize the state-dependent access probabilities for secondary users so that the spectrum resources can be efficiently and fairly shared by the secondary users in an opportunistic way. The secondary users' access is assumed to be controlled by a secondary management point. In [9], they design distributed spectrum sensing and access strategies for OSA under energy constraint on secondary users. But they have not considered sensing errors in the paper.

In this paper, we consider OSA when there are many SUs who want to access the primary spectrum. We propose a novel sensing and access scheme for cognitive radio network. The proposed sensing and access scheme is based on secondary channel quality. Besides, it is fully distributed scheme where no central controller or cooperation needed among the SUs. Each SU individually senses and accesses to the primary spectrum in every frame. Before sensing the primary spectrum, each SU will start its own timer with an initial value that is inversely proportional to the channel quality. The timer of a SU with the best channel condition will expire in the first place since it started from a smaller initial value. We assume that the sensing duration is the same for all the SUs. When sensing is perfect, only the best SU detects the primary spectrum available when the PU is actually idle. We begin with case of perfect sensing at the SUs. In Section IV we

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study on detection performance and the average throughput of the proposed scheme if there is sensing error.

On the other hand, an efficient scheme to select one among many candidates is proposed in the area of cooperative relaying networks [12]. In [12], the best relay is selected in a distributed manner by using channel quality information. We adopt the idea of timer used individually by each transmitter as like in [12].

II. SYSTEM MODEL

We consider a cognitive radio network with one primary link and L secondary links. The primary link consists of a PU transmitter (PU-TX) and a PU receiver (PU-RX). Each secondary link consists of a SU transmitter (SU-TX) and a SU receiver (SU-RX). The SU-TXs always have packets to transmit and they compete with each other for the primary spectrum.

The frame structure is designed for a cognitive radio network with periodic spectrum sensing [4][6]. Suppose the sensing duration is τ and the frame duration is T . At the beginning of each frame each, SU-TXs sense the primary spectrum independently for the duration τ . We assume that the PU is either active or idle in each frame of duration T . Let p denote the probability for which PU is idle.

If a SU-TX detects that the PU is idle, it proceeds to transmit its data in the rest of the frame. Otherwise, it must stay quiet and wait until the next frame to try again.

Let h_p and $h_i, i = 1, 2, \dots, L$ denote instantaneous channel gain of the link between PU-TX and PU-RX and between SU-TX _{i} and SU-RX _{i} . They are independent slowly varying flat Rayleigh fading random variables with variance σ_p^2 and $\sigma_{s,i}^2, i = 1, 2, \dots, L$, respectively. We assume that $\sigma_{s,i}^2 = \sigma_s^2$ for all i . The additive noise at all receiving nodes is modelled as zero-mean complex Gaussian random variables with variance σ_n^2 . We assume that channel is constant during the frame T .

At a time two or more nodes may transmit data using the primary spectrum. We assume zero interference tolerance at each of the primary and secondary receivers. Hence the rate vanishes if a collision between any nodes happens. Therefore only when one transmission pair uses spectrum at a time, effective rate is achieved. If the PU is active and no SU interferes with PU's transmission, an achievable rate is $R_0 = \log_2 \left(1 + \frac{h_p P_p}{\sigma_n^2} \right)$, where P_p is transmit power of PU. If any one SU-TX _{i} among L SU-TXs transmits data when the PU is idle, achievable rate at SU-RX _{i} is $R_i = \log_2 \left(1 + \frac{h_i P_s}{\sigma_n^2} \right)$, where P_s is transmit power of SU. We assume that all SU-TXs transmit with the same power.

The design objective is to determine, in each frame, which SU-TX transmits data when the PU is idle. In this paper, we consider to maximize the sum rate of PU and SU's.

III. CHANNEL QUALITY BASED SENSING AND ACCESS

A. Optimal Access

We consider perfect radio detection at the secondary users, i.e., the secondary users can detect whether or not the target

spectrum is active in each frame without any error. Obviously, the throughput is maximal if the SU-TX whose channel quality is best among L secondary links transmits data when the PU is idle. We set SUs in descending order of h_i , i.e., $h_1 > h_2 > \dots > h_L$. And especially we call SU-TX₁ and SU-RX₁ "best" SU in the sequel.

The optimal throughput is

$$\Theta_{\text{opt}} = \mathbb{E} \left[(1-p)R_0 + p \frac{T-\tau}{T} R_1 \right]. \quad (1)$$

B. Channel Quality Based Sensing And Access Under Perfect Sensing

In this subsection, we propose a channel quality based sensing and access policy for SUs to efficiently utilize the primary channel. Only the best SU out of L SUs transmits its data using the primary spectrum in the proposed scheme if there is no sensing error.

We assume that each SU-TX is aware of the channel quality of link between itself and the corresponding SU-RX. Each SU-TX and SU-RX exchanges RTS/CTS messages to establish communications. SU-TX estimates the channel gain from it to the SU-RX based on the information in CTS. We assume that the RTS/CTS are exchanged at the beginning of each frame. Compared with the total frame duration, the time needed to exchange RTS/CTS is short. We assume that RTS/CTS exchange time is negligible [11].

Here we adopt timer used individually by SU-TX [12]. At the beginning of frame, each SU-TX _{i} starts its own timer with an initial value,

$$D_i = \frac{\lambda}{h_i}, \quad (2)$$

where λ is a design parameter. D_i is inversely proportional to the channel quality h_i . As soon as timer is expired, each SU-TX _{i} starts to sense the primary spectrum. The best SU, SU-TX₁ spends the shortest waiting time before it starts spectrum sensing. Because the sensing duration is the same for all the SUs and sensing is perfect, $L-1$ SUs except the best SU sense that the primary channel is active. Actually the primary channel is occupied by the best SU. We assume that SU starts to transmit as soon as it finishes sensing. Figure 1 shows the operation of the proposed scheme under perfect sensing. The radio switch time from receive to transmit mode and processing time for sensing result are assumed to be negligible. The average throughput of the proposed scheme under perfect sensing is the following.

$$\Theta_{\text{perfect}} = \mathbb{E} \left[(1-p)R_0 + p \frac{T - \lambda/h_1 - \tau}{T} R_1 \right] \quad (3)$$

Although there is always time waste which results in degradation of throughput under the proposed scheme, the proposed scheme is fully distributed and easy to implement. It requires no central controller or no control channel.

It is worthy to note that increasing λ reduces the time fraction of transmission of SU if the primary is idle. However, smaller λ and longer τ results in a kind of *collision* among

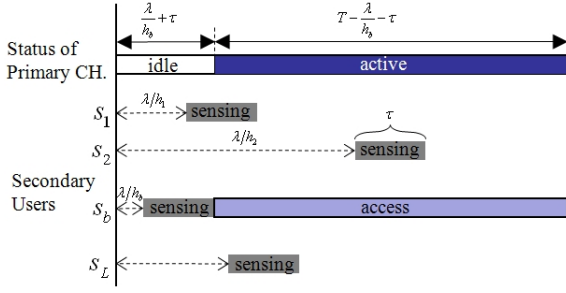


Figure 1. Channel quality-based sensing and access.

secondary users. If two or more SUs (especially, best SU₁ and second best SU₂) expire within a short interval, the two SUs sense that the primary is idle, and access the primary spectrum at the same time, resulting in collision. In this paper, we assume that λ is large enough so that the probability of this kind of collision is very low.

IV. PERFORMANCE ANALYSIS FOR IMPERFECT SENSING

We study the case of imperfect sensing in this section. Sensing error at SUs has an effect on the performance of SUs as well as PU. In our system model, L SUs, independently of each other, sense and make a decision whether or not the PU is idle. First we evaluate two probabilities of detection and false alarm. And then we study the average throughput of PU and SUs under imperfect sensing.

A. Individual detection performance

In the proposed scheme, each SU starts and finishes to sense the primary spectrum at different time. Even when PU is idle, the latter SUs may detect that the primary spectrum is not idle. Actually the primary spectrum is used by other SU who has better channel quality so that it has priority of access the primary spectrum.

We set out the following hypotheses :

- $\mathcal{H}_0$: The primary spectrum is idle.
- $\mathcal{H}_{1,p}$: The primary spectrum is active as a result from being used by PU.
- $\mathcal{H}_{1,s_j}$: The primary spectrum is active as a result from being used by SU-TX_j, $j = 1, 2, \dots, L$.

It is possible for SU-TX_j to use the primary spectrum at the sensing time of other SU-TX_i ($i = j + 1, \dots, L$) in our proposed scheme. We decompose typical alternative hypothesis $\mathcal{H}_1$ into $\mathcal{H}_{1,p}$, $\mathcal{H}_{1,s_j}$, $j = 1, 2, \dots, L$. We evaluate individual detection performance at each SU under hypotheses as stated above.

Energy detection is the most popular spectrum sensing scheme [4]. During sensing duration τ , N samples are collected to determine the state of the primary user. N is the number of samples, $N = \tau f_s$, where τ is the sensing time and f_s is the sampling frequency. The test statistic is given by $T_i(y) = \frac{1}{N} \sum_{k=1}^N |y_i(k)|^2$.

When energy detector is used, under $\mathcal{H}_0$, the received signal at the SU-TX_i is given by $y_i(k) = n_i(k)$. $y_i(k)$ denotes the discrete received signal of the k -th sample at the SU-TX_i, $1 \leq i \leq L$, $1 \leq k \leq N$. $n_i(k)$ is the AWGN with zero mean and variance $\mathbb{E}[|n_i(k)|^2] = \sigma_n^2$.

Let denote $s_{ip}(k)$ and $s_{ij}(k)$ the primary signal and the j -th secondary signal received at SU-TX_i, respectively. We assume that $s_{ip}(k)$ and $s_{ij}(k)$ are independent identical distributed (iid) circularly symmetric complex Gaussian signal with zero mean and variance $\mathbb{E}[|s_{ip}(k)|^2] = \sigma_{ip}^2$ and $\mathbb{E}[|s_{ij}(k)|^2] = \sigma_{ij}^2$. Under hypothesis $\mathcal{H}_{1,p}$ and $\mathcal{H}_{1,s_j}$, the received signal at the SU-TX_i are, respectively, given by

$$y_i(k) = s_{ip}(k) + n_i(k) \quad (4)$$

$$y_i(k) = s_{ij}(k) + n_i(k) \quad (5)$$

We make the following assumptions.

- (AS1) The primary signal $s_{ip}(k)$ is independent of the noise $n(k)$;
- (AS2) The secondary signal $s_{ij}(k)$ is independent of the noise $n(k)$;
- (AS3) The primary signal $s_{ip}(k)$ and the secondary signal $s_{ij}(k)$ are mutually independent of each other.

Two probabilities are of interest for spectrum sensing : probability of detection and probability of false alarm. Probability of false alarm is the probability of the algorithm falsely declaring the presence of primary signal under hypothesis $\mathcal{H}_0$, denoted by $P_f^{(i)}$. We have two kinds of detection : detection of primary signal under hypothesis $\mathcal{H}_{1,p}$ and of other secondary user's signal under hypothesis $\mathcal{H}_{1,s_j}$. The probability of detection at SU-TX_i is defined, under hypothesis $\mathcal{H}_{1,p}$, the probability of the algorithm correctly detecting the presence of primary signal, denoted by $P_{d,p}^{(i)}$. Similarly, the second probability of detection at SU-TX_i is defined as for the SU-TX_j's signal, denoted by $P_{d,s_j}^{(i)}$. Superscript (i) denotes i -th SU.

When energy detection is used, the PDF of $T_i(y)$ under each hypothesis can be approximated by a Gaussian distribution [4], using central limit theorem (CLT). Under hypothesis $\mathcal{H}_0$, $T_i(y)$ has mean $\mu_0^{(i)} = \sigma_n^2$ and variance $\sigma_0^{(i)} = \frac{\sigma_n^4}{N}$ and $T_i(y)$ under $\mathcal{H}_{1,p}$ has mean $\mu_{1p}^{(i)} = \sigma_{ip}^2 + \sigma_n^2$, variance $\sigma_{ip}^{(i)} = \frac{1}{N} (\sigma_{ip}^2 + \sigma_n^2)^2$. For a chosen threshold ϵ_i , the probability of false alarm and detection at SU-TX_i are given by

$$\begin{aligned} P_f^{(i)} &= \Pr [T_i(y) > \epsilon_i | \mathcal{H}_0] \\ &= \mathcal{Q} \left(\left(\frac{\epsilon_i}{\sigma_n^2} - 1 \right) \sqrt{\tau f_s} \right). \end{aligned} \quad (6)$$

$$\begin{aligned} P_{d,p}^{(i)} &= \Pr [T_i(y) > \epsilon_i | \mathcal{H}_{1,p}] \\ &= \mathcal{Q} \left(\left(\frac{\epsilon_i}{\sigma_{ip}^2 + \sigma_n^2} - 1 \right) \sqrt{\tau f_s} \right). \end{aligned} \quad (7)$$

$$\begin{aligned} P_{d,s_j}^{(i)} &= \Pr [T_i(y) > \epsilon_i | \mathcal{H}_{1,s_j}] \\ &= \mathcal{Q} \left(\left(\frac{\epsilon_i}{\sigma_{ij}^2 + \sigma_n^2} - 1 \right) \sqrt{\tau f_s} \right). \end{aligned} \quad (8)$$

where σ_{ip}^2 and σ_{ij}^2 are variance of the primary and j -th secondary signal received at SU-TX _{i} , respectively. And $\mathcal{Q}(x)$ is the complementary distribution function of the standard Gaussian, i.e., $\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{t^2}{2}\right) dt$.

We assume that a target detection probability of primary signal is same for all secondary users SU-TX _{i} , $i = 1, 2, \dots, L$. For a target probability of detection of primary signal, $\bar{P}_{d,p}$, the detection threshold ϵ_i of secondary user i can be determined by $\epsilon_i = (\sigma_{ip}^2 + \sigma_n^2) \left(\frac{\mathcal{Q}^{-1}(\bar{P}_{d,p})}{\sqrt{\tau f_s}} + 1 \right)$ for $i = 1, 2, \dots, L$. Therefore, the probability of false alarm for a target detection probability of primary signal at SU-TX _{i} , $\bar{P}_{d,p}$ is determined as follows

$$P_f^{(i)} = Q \left(\left(\frac{\sigma_{ip}^2}{\sigma_n^2} + 1 \right) \mathcal{Q}^{-1}(\bar{P}_{d,p}) + \frac{\sigma_{ip}^2}{\sigma_n^2} \sqrt{\tau f_s} \right). \quad (9)$$

Similarly, the detection probability of secondary user j at SU-TX _{i} under hypothesis $\mathcal{H}_{1,s_j}$ can be obtained for ϵ_i as follows

$$P_{d,s_j}^{(i)} = Q \left(\left(\frac{\sigma_{ip}^2 + \sigma_n^2}{\sigma_{ij}^2 + \sigma_n^2} \left(\frac{\mathcal{Q}^{-1}(\bar{P}_{d,p})}{\sqrt{\tau f_s}} + 1 \right) - 1 \right) \sqrt{\tau f_s} \right). \quad (10)$$

B. Throughput

In this subsection we present the average throughput for the primary user and for secondary users. Imperfect detection of SUs may interfere with the PU's transmission. In addition, under individual sensing and access without central controller, any mis-detection of SU interferes with other SU's transmission. We show how sensing error has an effect on the throughput of the PU and SUs. For each frame, depending on the PU's activity and the results of sensing by SUs, there exist five cases. One of the cases is that the PU is idle but no SU detects that primary spectrum is idle. In that case no throughput is attained. Therefore we present the throughput of four cases in the following.

Case 1: The PU is active and all SUs make a success of detection of primary signal. The PU transmits its own data without being interfered by SUs.

Case 2: The PU is active but one or more SUs fail to detect of primary signal. The PU successfully transmits its own data before a SU starts to access the primary spectrum as a result of mis-detection.

Case 3: The PU is idle and just one among L SUs accesses the primary spectrum. The SU successfully transmits its own data using the primary spectrum and attains data rate.

Case 4: The PU is idle and two or more SU access the primary spectrum.

Case 5: The PU is idle but no SU detects that primary spectrum is idle and keeps silent.

In Case 1 and 2 we obtain the average throughput of PU. The secondary's throughput is attained in Case 3 and 4. It is trivial that no throughput is attained in Case 5. The probabilities for which cases happen and the throughput in each case are presented in the next subsection.

1) Case 1: We assume that PU-TX transmits with a constant power P_p and SU-TXs with P_s . In case 1 where PU is active and no miss detection happens, the rate of primary, R_0 is fully achieved during frame T . All SUs detect primary signal without error in case 1, the probability of case 1 is $\prod_{j=1}^L P_{d,p}^{(j)}$. The average throughput in case 1 is given by

$$\Theta_1 = (1-p) \mathbb{E}[R_0] \prod_{j=1}^L P_{d,p}^{(j)} = (1-p) \mathbb{E}[R_0] (\bar{P}_{d,p})^L. \quad (11)$$

2) Case 2: PU is active but one or more SUs fail to detect of primary signal in this case. We consider case 2 by dividing into L sub-cases. The i -th sub-case represents that the SU-TX _{i} first fails to detect primary signal. We describe in detail the first sub-case in the following. The best SU-TX₁ starts sensing first of all after λ/h_1 from beginning of frame and finishes at $\lambda/h_1 + \tau$. The best SU-TX₁ mis-detects and accesses primary spectrum with probability $1 - P_{d,p}^{(1)}$. Mis-detection and access for primary spectrum results in collision. Hence, R_0 is attained by PU during $\lambda/h_1 + \tau$, but after that, the rate vanishes under assumption of zero interference tolerance because of interference from SU-TX₁. The average throughput in this sub-case is given by

$$\Theta_{2-1} = (1-p) \mathbb{E} \left[R_0 \frac{\lambda/h_1 + \tau}{T} \right] (1 - P_{d,p}^{(1)}). \quad (12)$$

In the proposed scheme, SU-TXs start sensing at different time one after another depending on their channel quality. All SUs sense during τ . As a result, SU-TXs finish and access (if sensing result is $\mathcal{H}_0$) in order. Suppose that from the best SU-TX₁ to SU-TX _{$i-1$} successfully detect primary signal but SU-TX _{i} fail to detect. The PU attains R_0 before SU-TX _{i} finishes sensing at $\lambda/h_i + \tau$. This happens with probability $\prod_{j=1}^{i-1} P_{d,p}^{(j)} (1 - P_{d,p}^{(i)}) = (\bar{P}_{d,p})^{i-1} (1 - \bar{P}_{d,p})$. Therefore the average throughput in case 2 is given by

$$\Theta_2 = \frac{(1-p)}{T} \sum_{i=1}^L \mathbb{E} \left[R_0 \left(\frac{\lambda}{h_i} + \tau \right) \right] (\bar{P}_{d,p})^{i-1} (1 - \bar{P}_{d,p}). \quad (13)$$

3) Case 3: The PU is idle and just one among L SUs accesses the primary spectrum in case 3. The SU successfully transmits its own data using the primary spectrum and attains data rate. Because of zero interference tolerance at receivers, the achievable rate is attained only if one transmitter accesses the primary spectrum. For case 3, one of SUs, SU-TX _{i} , assesses successfully the primary spectrum. The probability for which only SU-TX _{i} accesses and the rest of SUs does not access is $\prod_{j=1}^{i-1} P_f^{(j)} (1 - P_f^{(i)}) \prod_{j=i+1}^L P_{d,s_i}^{(j)}$, $i = 1, 2, \dots, L$.

The SU-TX _{i} transmits data during $\left(T - \frac{\lambda}{h_i} - \tau\right)$ of frame T with achievable rate $R_i = \log_2 \left(1 + \frac{h_i P_s}{\sigma_n^2}\right)$.

$$\Theta_3 = \frac{p}{T} \sum_{i=1}^L \mathbb{E} \left[R_i \left(T - \frac{\lambda}{h_i} - \tau \right) \right] \prod_{j=1}^{i-1} P_f^{(j)} (1 - P_f^{(i)}) \prod_{j=i+1}^L P_{d,s_i}^{(j)}. \quad (14)$$

4) *Case 4:* The PU is idle and two or more SU access the primary spectrum in case 4. Case 4 is divided into $L - 1$ sub-cases. The i -th sub-case represents that the SU-TX _{i} first senses that the primary spectrum is idle. Suppose that SU-TX _{i} first detect that primary spectrum is idle. The SU-TX _{i} begins to transmit data using the primary spectrum at $\frac{\lambda}{h_i} + \tau$. The probability for which SU-TX _{i} first detects that primary spectrum is idle is $\prod_{j=1}^{i-1} P_f^{(j)} (1 - P_f^{(i)})$. While SU-TX _{i} transmits data using the primary spectrum, other SU-TX _{j} ($j > i$) may access the primary spectrum. This happens when the outcome of sensing at the SU-TX _{j} is that the PU is idle. However, the primary spectrum is not idle because SU-TX _{i} uses the primary spectrum already. The SU-TX _{j} fails to detect the SU-TX _{i} with probability $\prod_{k=i+1}^{j-1} P_{d,si}^{(k)} (1 - P_{d,si}^{(j)})$. In case 4- i , SU-TX _{i} successfully transmits its data using primary spectrum before other SU-TX _{j} , $j = i + 1, \dots, L$ interferes with SU-TX _{i} . SU-TX _{j} begins to access the primary spectrum at $\frac{\lambda}{h_j} + \tau$ if it fails to detect SU-TX _{i} . Therefore, the time duration of successful transmission of SU-TX _{i} is $\frac{\lambda}{h_j} - \frac{\lambda}{h_i}$.

$$\Theta_{4-i} = p \frac{1}{T} \sum_{j=i+1}^L \mathbb{E} \left[R_i \left(\frac{\lambda}{h_j} - \frac{\lambda}{h_i} \right) \right] \times \prod_{k=1}^{i-1} P_f^{(k)} (1 - P_f^{(i)}) \prod_{k=i+1}^{j-1} P_{d,si}^{(k)} (1 - P_{d,si}^{(j)}), \quad (15)$$

for $i = 1, 2, \dots, L - 1$.

$$\Theta_4 = \sum_{i=1}^{L-1} \Theta_{4-i}. \quad (16)$$

In (16), $\mathbb{E} \left[R_i \left(\frac{\lambda}{h_j} - \frac{\lambda}{h_i} \right) \right]$ is given by the following equations:

$$\mathbb{E} \left[R_i \left(\frac{\lambda}{h_j} - \frac{\lambda}{h_i} \right) \right] = \int \int_{h_i, h_j < h_i} R_i \left(\frac{\lambda}{h_j} - \frac{\lambda}{h_i} \right) f_{ij}(h_i, h_j) dh_j dh_i, \quad (17)$$

where $f_{ij}(h_i, h_j)$ is joint PDF of h_i and h_j (the analytical expression is not given here due to the space limitations).

5) *Total Average Throughput:* Finally, we obtain the total average throughput for imperfect sensing by summation of the average throughput of PU and SUs.

$$\Theta_{\text{Imperfect}} = \Theta_1 + \Theta_2 + \Theta_3 + \Theta_4. \quad (18)$$

V. NUMERICAL EXAMPLE

In this section, we examine the performance of the proposed scheme for the following systems parameters. We set the probability that the primary is idle $p = 0.9$, frame duration $T = 100$ ms and $f_s = 5000s^{-1}$. Sensing duration, τ , is 5 ms and $\lambda = 10$. We assume that primary's transmit power and all SUs' transmit power is same and they are equal to 1 ($P_p = P_s = 1$). The instantaneous channel gain power of all links of SUs and PU are set to 1, i.e. $\sigma_p^2 = 1$, $\sigma_{si}^2 \equiv \sigma_s^2 = 1$ for $i = 1, 2, \dots, L$ and $\sigma_n^2 = 1$.

Figure 2 shows the average throughput of the proposed scheme under perfect sensing and under imperfect sensing as a function of the number of SUs. In figure 2, under perfect sensing, the average throughput under perfect sensing increase as the number of SUs (L) increases just like as the optimal case. A difference between the average throughput of the proposed scheme and the optimal throughput is almost constant with varying the number of SUs. The difference comes from λ . For imperfect sensing in figure 2, we set target detection probability of primary signal $\bar{P}_{d,p}$ is set 0.95 and 0.90. Figure 2 shows that the average throughput under imperfect sensing is concave for the number of SUs. There exists an optimal number of SUs to maximize the average throughput if there are sensing error in the proposed distributed scheme. Especially, smaller target detection error results in deterioration of the average throughput. It is noticed that the optimal number of SUs for these two curves are different. This is explained as follows. As the target detection probability for primary signal is smaller, the detection probabilities of other secondary signal are also smaller. Therefore it is likely to the latter SUs to fail sensing that the primary spectrum is already used by the earlier SU.

Figure 3 shows the average throughput of the proposed scheme as a function of sensing time τ . For perfect sensing and optimal case, the average throughput is decreasing for sensing duration τ . It is obvious that the average throughput of SUs is decreasing for sensing duration while that of PU is constant over varying sensing duration if there is no sensing error. For imperfect sensing where target detection probability is 0.95, figure 3 shows that the average throughput is a concave function with respect to τ .

Figure 4 shows the average throughput as a function of design parameter λ . The average throughput of the proposed scheme is decreasing for λ . It is obvious that increasing λ reduces the time fraction of transmission of each SU if the primary is idle. Therefore we need to have λ as small as possible not to lose the opportunity of access the primary spectrum. However it is noted that too small λ causes a collision between SUs who has similar channel quality.

VI. CONCLUSION

In this paper, we consider OSA when there are many SUs who want to access the primary spectrum. We propose a distributed sensing and access scheme, which is based on secondary channel quality. We study the performance of the proposed scheme of perfect sensing and imperfect sensing at the SUs. For the case of imperfect sensing we evaluate individual detection performance. The average throughput of the proposed scheme under imperfect sensing is a concave function of the number of SUs. Too many SUs causes deterioration of the average throughput. We show that there exists the optimal number of SUs to maximize the average throughput for a given target detection probability when imperfect sensing.

We need to design a parameter λ considering a tradeoff. Increasing λ at each SU reduces the time fraction of transmission of SU if the primary is idle and, as a result, deteriorates the

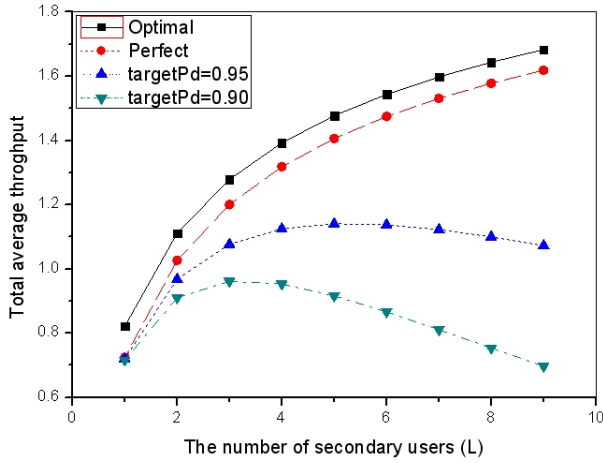


Figure 2. The average throughput vs. the number of secondary users L : $\tau = 5$ ms, $\lambda = 10$, $\bar{P}_{d,p} = 0.9$ and 0.95 .

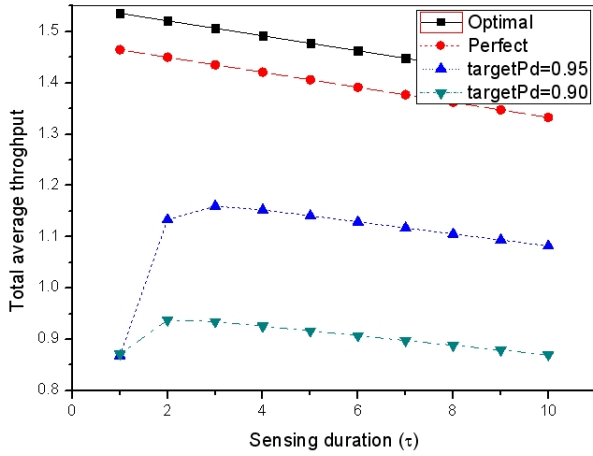


Figure 3. The average throughput vs. sensing duration τ : $L = 5$, $\lambda = 10$, $\bar{P}_{d,p} = 0.9$ and 0.95 .

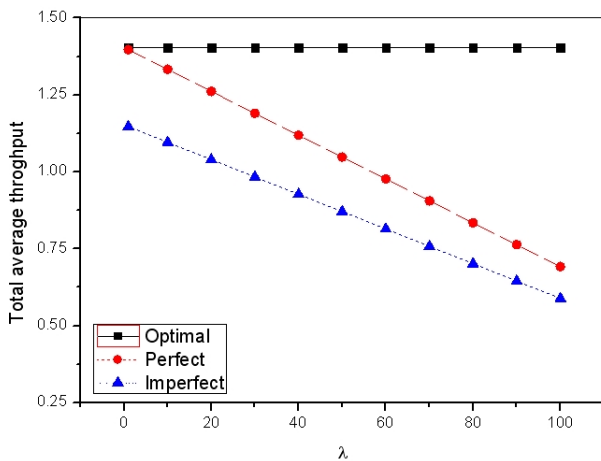


Figure 4. The average throughput vs. λ : $\tau = 5$ ms, $\bar{P}_{d,p} = 0.95$.

average throughput. However too small λ causes a collision between SUs who have similar channel quality. There is tradeoff between the time opportunity of having access to the primary signal and the probability of collision between two SUs. In this paper, we assume that λ is large enough so that the probability of this kind of collision is very low. As a future work, we plan to consider analytically the impact of λ on the performance.

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