Sensing-Throughput/Positioning Tradeoff in Indoor Cognitive Radio Networks

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Abstract—This paper evaluates the performance of indoor cognitive networks in terms of the throughput and the positioning, according to the spectrum sensing time. A better sensing quality can be obtained by using a longer sensing time. The better sensing quality of a secondary user (SU), the more accurate information about a primary user (PU) positioning. However, there exists a tradeoff between the sensing quality and the achievable throughput. In the previous works, the achievable throughput has been derived under the assumption that the PU has a constant occupancy state during the entire frame duration. Actually, however, the state of PUs varies during the entire frame duration. We exploit a cooperative spectrum sensing for better observation on the PU positioning. Simulation results show that the proposed scheme gets more reliable positioning performance and better achievable throughput compared to those of previous works.

Keywords—Indoor cognitive radio, indoor PU positioning, cooperative spectrum sensing, sensing-throughput tradeoff

I. INTRODUCTION

Positioning information detected by means of wireless communication devices is widely used in some application scenarios such as military action, geography, navigation and deployment of vehicles. Today's researches are more focusing on detecting positioning information with high accuracy and reliability in indoor environments [1]. To satisfy accuracy and reliability about positioning information, we propose an indoor cognitive radio technology [2], [3]. The basic idea of indoor cognitive radio networks is that SUs can opportunistically access the spectrum of PUs by detecting positioning information and spectrum band utilization of PUs in indoor environments.

To detect the accurate positioning information, a spectrum sensing is the important technology in indoor cognitive radio networks [4]. There are two parameters associated with the spectrum sensing: detection probability and false alarm probability. The higher detection probability, the better the PUs can be protected. As the detection probability is related with a sensing time, the longer sensing time leads to higher detection probability. However, from the SUs' perspective, the lower the false alarm probability, the more chances the channel can be reused when it is available, thus the higher the achievable throughput for the SUs. Indeed, SUs would be preferable to reduce the sensing time, and to increase the frame duration as much as possible, since the sensing time represents a lost transmission opportunity. Thus, there exists a fundamental tradeoff between the sensing quality and the achievable throughput in the cognitive radio networks.

In [5] and [6], the authors considered this tradeoff and showed the existence of an optimal sensing time for a target detection probability. However, the achievable throughput equations derived in [5] and [6] were based on the assumption that the PU has a constant occupancy state during the entire frame duration. In reality, the primary user may start or stop occupying the channel at any time, especially when the primary user network has a high traffic or when a long SU's frame duration is used. Also, due to the indoor penetration loss and the indoor fading, the PU has a dynamic traffic model in indoor cognitive radio networks. Therefore, the state of the PU varies during entire frame duration. In [7], the authors have solved the sensing-throughput tradeoff in the dynamic PU traffic model. It would be more realistic traffic model than that of [5] and [6]. However, only one SU senses the PU traffic model in [7]. It is difficult for one SU to detect the dynamic PU traffic model in indoor cognitive radio networks. To overcome this problem, we adopt the cooperative spectrum sensing for obtaining higher detection probability [8]. A cooperative spectrum sensing provides significant performance improvement over single-user techniques as well as lower complexity for the individual SU at the cost of a small increase in communication between the SUs and the fusion center.

In this paper, we study the problem of sensing-throughput/positioning tradeoff for cognitive radio networks. Particularly, we are interested in the problem of designing the sensing time to maximize the achievable throughput for the SUs under the dynamic PU traffic model. Also, we exploit the cooperative spectrum sensing for solving optimal sensing time in indoor cognitive radio networks. The contribution of this paper is that by considering the PU traffic in the sensing-throughput/positioning tradeoff problem, a more realistic cognitive radio network scenario is established. Results show that the SUs get more positioning information and achievable throughput when the cooperative spectrum sensing is considered despite the dynamic PU traffic model.
II. SYSTEM MODEL

A. PU Dynamic Traffic Model

We consider an indoor cognitive radio network where SUs try to opportunistically access a given frequency band assigned to a licensed PU, whenever the PU is not using that band. The state of the PU can be assumed to change over the frame duration. Based on the assumption, the dynamic PU traffic model can be composed of the following four cases: the hypothesis \( H_{00} \) that the licensed PU channel is idle over the entire frame duration, the hypothesis \( H_{01} \) that the licensed PU channel is idle during the sensing time period, then become busy state at the transmission period, the hypothesis \( H_{11} \) that the licensed PU channel is busy during the entire frame duration, and the hypothesis \( H_{00} \) that the licensed PU channel is busy during the sensing time period, then become idle state at the transmission period. These cases are shown in Fig. 1.

The PU traffic model is modeled as independent identically distributed 1-0 random process, where ‘1’ stands for a busy channel and ‘0’ stands for a idle channel. Exponential holding time is assumed for each state, with mean parameter \( \lambda \) for ‘1’ and mean parameter \( \mu \) for ‘0’ [9]. Therefore, at any time instant, the probability that the channel is busy is given by \( p_b = \lambda / (\lambda + \mu) \), and the probability that the channel is idle is given by \( p_i = 1 - p_b \). The transition probability of the channel is given by [7]:

\[
p(T_s) = \begin{pmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{pmatrix} = \frac{1}{\lambda + \mu} \begin{pmatrix} \lambda + \mu e^{(\lambda + \mu)T_s} & \mu e^{(\lambda + \mu)T_s} \\ \lambda e^{(\lambda + \mu)T_s} & \lambda + \mu e^{(\lambda + \mu)T_s} \end{pmatrix}
\]  

(1)

where \( T_s \) means that the channel state may change every sampling intervals of \( T_s \) seconds. We assume that the PU state transition occurs at most once within each frame duration. Actually, there is the case of more transitions in one frame but this case do not consider in this paper. Denote \( M \) as the total number of samples in the frame duration. The total number of samples collected from the sensing time period is \( I \). Let the sample where the PU change the idle state and the busy state be \( a \) and \( b \) at the licensed channel, respectively. By using the transition probabilities, the probabilities of each hypothesis can be derived as

\[
P(H_{00}, T_s) = p_a p_{00}^a (T_s)
\]

\[
P(H_{01}, T_s) = \sum_{i=1}^{M-1} p_i p_{00}^i (T_s) p_{01}^a (T_s) p_{11}^{M-i-1} (T_s)
\]

\[
P(H_{10}, T_s) = \sum_{i=1}^{M-1} p_i p_{10}^i (T_s) p_{10}^a (T_s) p_{00}^{M-i-1} (T_s)
\]

\[
P(H_{11}, T_s) = p_b p_{11}^a (T_s)
\]

(2)

B. Spectrum Sensing

To sense the presence or absence of the PU signal, the SUs use an energy detector with sampling frequency \( f_s \). Although the PU traffic model is dynamic, we assume that the sensing time period is sufficiently short so that the PU is permanently either busy state or idle state during the whole sensing stage. Thus, the spectrum sensing process is a binary hypothesis testing problem given by

\[
Y = \begin{cases} \sum_{i=1}^{I} n_i^2, & H_{00}, H_{01} \\ \sum_{i=1}^{I} (s_i + n_i)^2, & H_{10}, H_{11} \end{cases}
\]

(3)

where \( n_i \) are the samples of the additive white Gaussian noise (AWGN), \( s_i \) are the samples of the PU signal, \( Y \) is the output of the energy detector. As the state of the hypotheses \( H_{00} \) and \( H_{01} \) are same as idle state in sensing time period, the output of the detector contains only noise. On the contrary, the hypotheses \( H_{10} \) and \( H_{11} \) indicate the busy state in sensing time period. Then, the detection probability and the false alarm probability are derived as,

\[
P_d(\epsilon, I) = P(Y > \epsilon | (H_{10} \mid H_{11}))
\]

\[
P_f(\epsilon, I) = P(Y > \epsilon | (H_{00} \mid H_{01}))
\]

(4)

respectively, where \( P_d \) is the detection probability, \( P_f \) is the false alarm probability, and \( \epsilon \) is the detection threshold.

III. SENSING-THROUGHPUT TRADEOFF

In this section, we formulate the tradeoff between the sensing quality and the achievable throughput of the SUs. Denote \( \tau \) as the sensing time duration and the \( T \) as the frame duration, respectively. After the spectrum sensing process (3), each SU decides the PU’s state whether the PU is idle or busy throughout (4). If the SUs decide that the PU is absent from the licensed channel, then secondary transmission begin. Due to the dynamic PU traffic, however, the secondary transmission would come into collision with the PU signal. Thus, the channel capacity is affected by the PU traffic, and
can be formulated based on the 4 hypotheses. For the hypothesis \( H_{0b} \), the channel capacity is not affected by the PU traffic. Thus, it can be easily derived using Shannon capacity theorem as

\[ C_{0b} = \log_2 (1 + \gamma_s) \]  

(5)

where \( \gamma_s \) represents the signal-to-noise ratio (SNR) of the secondary transmission and \( \gamma_p \) represents the PU's SNR received at the SUs. In \( H_{01} \), the PU signal is absent during the sensing time period, but it arrive during the transmission period. Thus, the channel capacity becomes

\[ C_{1b} = \log_2 \left( 1 + \frac{\gamma_s}{1 + \frac{\gamma_s}{2} \gamma_p} \right), \quad I + 1 \leq b \leq J \]  

(6)

where the \( I + 1 \leq b < J \) represents the case when the PU arrives during the transmission period. If \( b \) is equal to \( J \), the PU remains absent during the transmission period, which is the same as \( C_{0b} \). In \( H_{11} \), the PU remain present during the transmission period. Thus, the channel capacity becomes

\[ C_{1i} = \log_2 \left( 1 + \frac{\gamma_s}{1 + \frac{\gamma_s}{2} \gamma_p} \right) \]  

(7)

In \( H_{10} \), the PU signal is present during the sensing time period, but it leaves the channel during the transmission period. Thus, the channel capacity becomes

\[ C_{10} = \log_2 \left( 1 + \frac{\gamma_s}{1 + \frac{\gamma_s}{2} \gamma_p} \right), \quad I + 1 \leq a \leq J \]  

(8)

where \( I + 1 \leq a < J \) represents the case when the PU leaves the channel during the transmission period. If \( a \) is equal to \( J \), the PU remains present during the transmission period, which is the same as \( C_{11} \).

In order to maximize the achievable throughput, from the SUs perspective, the SUs would prefer to decrease the sensing time period \( \tau \) and to increase the frame duration \( T \), since longer sensing time lead to lower transmission opportunity. However, if the sensing time \( \tau \) asymptotically approach to zero, the SUs cannot guarantee that sensing results are under a given threshold. Therefore, it is important to appropriately adjust the sensing time \( \tau \) in order to obtain the maximum achievable throughput. Also, the SUs satisfy certain detection probability where the PU is sufficiently protected. The maximum achievable throughput by the SUs can be derived as

\[
\max_{\tau} R(\varepsilon, I) = R_{H_{0a}}(\varepsilon, I) + R_{H_{1a}}(\varepsilon, I) + R_{H_{0i}}(\varepsilon, I) + R_{H_{1i}}(\varepsilon, I) \]  

(9)

\[
\text{s.t.} \quad P_d(\varepsilon, I) \geq \overline{P_d} \]

where

\[
R_{H_{0a}}(\varepsilon, I) = C_{0a} \cdot P \left( H_{0a}, T \right) \cdot \left( 1 - P_{f}(\varepsilon, I) \right) \frac{T - \tau}{T} 
\]

\[
R_{H_{1a}}(\varepsilon, I) = C_{0a} \cdot P \left( H_{1a}, T \right) \cdot \left( 1 - P_{f}(\varepsilon, I) \right) \frac{T - \tau}{T} 
\]

\[
R_{H_{0i}}(\varepsilon, I) = C_{1i} \cdot P \left( H_{0i}, T \right) \cdot \left( 1 - P_{d}(\varepsilon, I) \right) \frac{T - \tau}{T} 
\]

\[
R_{H_{1i}}(\varepsilon, I) = C_{1i} \cdot P \left( H_{1i}, T \right) \cdot \left( 1 - P_{d}(\varepsilon, I) \right) \frac{T - \tau}{T} 
\]

and \( \overline{P_d} \) is the target detection probability with which the PU is defined as being sufficiently protected. In order to solve (9), we use the exhaustive search method over \( \tau \).

IV. SIMULATION RESULTS

In this section, we represent computer simulation results to evaluate the sensing-throughput tradeoff. For all result, the total frame duration is set to 10ms, and the sampling frequency \( f_s \) is set to 10kHz. The additive noise is a zero-mean circularly symmetric complex Gaussian noise process. We assume the SNR of the secondary transmission \( \gamma_s = 3 \text{dB} \), and \( \gamma_p = -10 \text{dB} \) in Fig. 3 and Fig. 4. Also, we use OR-rule for the cooperative spectrum sensing scheme and set the four SUs sensing the licensed channel. For simplicity, we assume that the received SNRs for PU at each SU are all equal. The conventional PU model in this graph means the static PU traffic model during entire SU’s frame duration.

Fig. 2 shows the detection probability \( P_d \) versus the SNR \( \gamma_p \) under different PU traffic model. Assume the sensing time \( \tau = 1 \text{ms} \), and the false alarm probability \( P_f = 0.1 \). Higher detection probability means that the SUs can detect more accurate positioning information of the PU in indoor cognitive radio networks. Also, it is important to satisfy the high detection probability in a low SNR area since the indoor positioning network is mainly low SNR environment. To satisfy the detection probability over 0.9, the SUs for the conventional model and the proposed model require a SNR of \(-3.9 \text{dB} \) and
different PU traffic model using OR-rule.

Simulations results show that the optimal sensing time achieving the highest achievable throughput for the SUs under the constraint that the false alarm probability is sufficiently guaranteed.

Fig 3. shows the ROC curve under the different PU traffic models. As the ROC curve compares the detection probability and the false alarm probability in cognitive radio researches, it could be criterion which detectors have a better sensing quality. The detection probability in proposed PU model is higher than the detection probability in conventional PU model when the false alarm is same. Therefore, the cooperative spectrum sensing scheme when OR-rule is applied has better sensing quality than the single spectrum sensing scheme despite the dynamic PU traffic.

Fig 4. shows the achievable throughput versus the sensing time for the secondary networks. We assume the SNR $\gamma_p = -10$dB and the target detection probability $P_d = 0.9$. It can be observed from the figure that the achievable throughput when the cooperative spectrum sensing scheme is applied in the proposed PU model is higher than when the single spectrum sensing scheme is applied in the conventional PU model.

V. CONCLUSION

In this paper, we study the sensing-throughput/positioning tradeoff problem by considering the dynamic PU traffic in indoor cognitive radio networks. In particular, we study the problem of designing the sensing time period to maximize the achievable throughput for the SUs under the constraint that the sensing quality is sufficiently guaranteed. Simulation results show that the optimal sensing time achieving the highest throughput while maintaining 90% detection probability is 2.8ms in dynamic PU traffic model when four SUs cooperatively sense the channel using the OR-fusion rule.

From this sensing time point, the SUs can obtain the maximum achievable throughput, maintaining a certain detection probability of the indoor positioning information.

REFERENCES