Comparison of Cooperative Spectrum Sensing Strategies in Distributed Cognitive Radio Networks

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***Abstract*—Cooperative spectrum sensing has been proposed to significantly improve spectrum sensing accuracy by taking advantage of the cooperation among secondary users (SUs), but also this incurs some sensing cost. In this paper, we present a cooperative spectrum sensing model with consideration to spectrum sensing cost in distributed cognitive radio networks where each SU aims to maximize its utility. Under the scenario with selfish SUs, we formulate cooperative spectrum sensing as a non-cooperative game and obtain the mixed strategy Nash equilibrium of the formulated spectrum sensing game by deriving the sensing probabilities of SUs. Under the scenario with limited collaboration of SUs, we formulate cooperative spectrum sensing as a nonlinear optimization problem and derive the optimal sensing strategy of SUs by using our proposed Newton-Raphson based algorithm. Numerical results demonstrate that SUs with limited collaboration are able to achieve much better performance than the outcome of the Nash equilibrium and by choosing the optimal sensing strategy SUs are able to maximize their utility, which is an effective tradeoff between SU throughput and sensing cost.**

I. Introduction

Spectrum sensing is one of the key enabling functionalities for cognitive radio networks (CRNs) where secondary users (SUs) are allowed to opportunistically utilize the potentially unused frequency band without causing harmful interference to primary users (PUs). In essence spectrum sensing is a process of sampling PUs' signal and making a decision on the presence or absence of licensed users over this particular spectrum band. Cooperative spectrum sensing has been proposed to significantly improve the accuracy and reliability of spectrum sensing by taking advantage of cooperation among SUs while increasing spectrum sensing cost and overhead.

Cooperative spectrum sensing has attracted a lot of attentions in the research community [1-12]. An extensive survey on cooperative spectrum sensing in CRNs can be referred to in [1-2]. The benefits of SUs' cooperation in CRNs have been shown in the literature, in terms of the improvement of detection performance [3] or the reduction of detection time [4]. In [5] [6], the tradeoff between spectrum sensing time and SU throughput was jointly optimized by obtaining the optimal sensing time and number of cooperative SUs. Cooperative spectrum sensing cost, particularly energy consumption, has been studied in [7][8]. In [7] the tradeoff between spectrum sensing cost and missed spectrum opportunities was studied while the authors of [8] investigated a balance between energy consumption and system throughput. In [9-11] cooperative spectrum sensing was studied from the game theoretic point of view. In [9] a coalitional game was formulated to investigate the tradeoff between missed detection probability and false alarm probability. In [10][11] the authors studied spectrum sensing games where selfish SUs may choose to share their spectrum sensing results or not. In [12] a non-cooperative spectrum sensing game was proposed to optimize SU throughput by considering the tradeoff between the reduction of sensing time by cooperation and transmission time.

Our work, however, is different from the previous work. We investigate the sensing strategies for cooperative SUs taking into account both the decrease of false alarm probability due to cooperation and the sensing cost incurred such as energy consumption. For a given detection probability, if more SUs cooperate with each other, the probability of false alarm decreases, which means that SUs are able to identify more spectrum opportunities, but also those SUs doing sensing incur spectrum sensing cost. In this paper we study cooperative spectrum sensing strategies in order to make a tradeoff between the gain of cooperation and spectrum sensing cost.

In this paper we present a cooperative spectrum sensing model with consideration to spectrum sensing cost in distributed CRNs. In CRNs each SU aims to maximize its utility while guaranteeing the probability of missed detection below a given threshold. Under the scenario with selfish SUs, we formulate cooperative spectrum sensing as a non-cooperative game and obtain the mixed strategy Nash equilibrium of the formulated spectrum sensing game by deriving the sensing probabilities of SUs. Under the scenario with limited collaboration, we formulate it as a nonlinear optimization problem and derive the optimal sensing strategy of SUs by using the proposed algorithm. Numerical results demonstrate that SUs with limited collaboration are able to achieve much better performance than the outcome of the Nash equilibrium and by choosing the optimal sensing strategy SUs are able to maximize their utility, which essentially is the tradeoff between SU throughput and sensing cost.

The remainder of this paper is organized as follows. In Section II the system model is presented. The sensing strategies under the scenario with selfish SUs and with limited collaboration of SUs are investigated in Section III and IV respectively. The numerical results and discussion are presented in Section V. Finally section VI concludes this paper.

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II. System Model

A. System Model

In this paper we consider an opportunistic spectrum access model where one channel of the primary system can be divided into M sub-channels in CRNs, as shown in Fig.1. A PU needs one channel for its service while a SU can only access one sub-channel at a time when the primary user is detected to be absent. Such assumption is widely used in the literature [12][13]. One example is that a TV channel with the bandwidth of 6 MHz may be divided into multiple sub-channels. SUs operate in a time slot manner. Before transmitting over a particular sub-channel, a SU has to spend a fixed duration of time on performing spectrum sensing to detect the presence or absence of a PU. SUs equipped with energy detectors can jointly sense the primary channel and share their sensing results over the signaling channel, also referred to as the common control channel [11][12].

Through cooperation among SUs, the probability of false alarm can be improved to some degree for a given threshold of detection probability. It has been shown in [3][4] that the more SUs participate in cooperative sensing, the better sensing performance can be achieved. However, spectrum sensing may incur some sensing cost which consists of energy consumption for spectrum sensing such as signal processing and reporting sensing results over the common control channel [7][8][10][11]. Therefore, essentially there exists a fundamental tradeoff between the improved sensing performance and sensing cost.

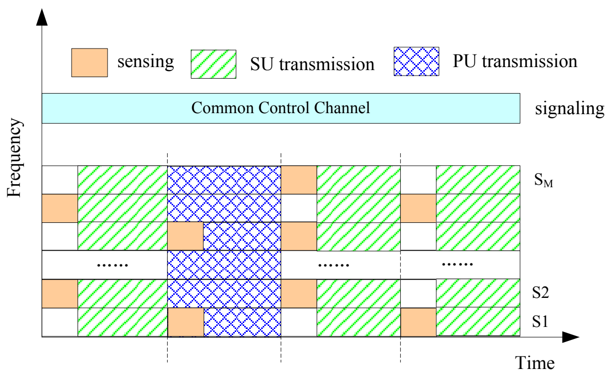

Fig. 1. Sensing Strategies under Different Scenarios

Similar to [12] it is assumed that there are $N \leq M$ SUs in CRNs where SUs would like to access different channels. The sensing results of SUs are broadcast in order to share them with others [10][11][12]. In such a case, other SUs may be able to overhear the sensing results from the SUs doing spectrum sensing and take free rides. Hence SUs might take advantage of that and refuse to perform spectrum sensing to save their energy and avoid any sensing cost. However, from the perspective of networks, SUs are encouraged to perform spectrum sensing in order to improve channel efficiency. Hence we assume that no sensing of SUs might result in some penalties imposed by the network operator. In CRNs all SUs aim to maximize their utility which is considered as the tradeoff between SUs throughput and spectrum sensing cost.

B. Cooperative Spectrum Sensing

The spectrum sensing is considered as a binary hypothesis testing problem: hypothesis H_0 when a PU signal is absent or inactive and hypothesis H_1 when a PU signal is present. For the energy detection technique, the test statistic for the energy detector is compared with a detection threshold, λ, to decide the presence or absence of the primary signal. Denote γ as the received average SNR of the PU's signal measured at the SU side of interest under hypothesis H_1. Under the Rayleigh fading channel assumption, the average probability of detection of a single SU sensing is given by [3],

$$\begin{aligned} P_d = {} & e^{-\frac{\lambda}{2}} \sum_{p=0}^{m-2} \frac{1}{p!}\left(\frac{\lambda}{2}\right)^p + \left(\frac{1+\gamma}{\gamma}\right)^{m-1} \\ & \times \left(e^{-\frac{\lambda}{2(1+\gamma)}} - e^{-\frac{\lambda}{2}} \sum_{p=0}^{m-2} \frac{1}{p!} \left(\frac{\lambda\gamma}{2(1+\gamma)}\right)^p \right) \end{aligned} \tag{1}$$

The average probability of false alarm is given by [3],

$$P_f = \frac{\Gamma(m, \frac{\lambda}{2})}{\Gamma(m)} \tag{2}$$

where m denotes the product of the spectrum sensing time and channel bandwidth. $\Gamma(a, x)$ is the incomplete gamma function, and $\Gamma(a)$ is the gamma function.

It is assumed that a SU performing spectrum sensing has to report the value of the PU signal measurement over the signaling channel so as to share it with others. In this way cooperative spectrum sensing between distributed SUs can be done [11][12]. The detection threshold for the measurements will be adaptively adjusted by considering the number of SUs performing spectrum sensing. The OR decision rule is used to make the final decision by each SU. Note that our model can be readily extended to different cooperative spectrum sensing schemes, such as soft or hard decision as well as different fusion rules.

We also assume that SUs have the same SNR values of the PU signal [6][12]. Hence each SU has the same P_f and P_d. For a given time slot, assuming K SUs doing spectrum sensing, the false alarm probability of cooperative spectrum sensing based on the OR rule is given by

$$Q_f^K = 1 - \prod_{i=1}^{K} (1 - P_{f,i}(\lambda_K)) \tag{3}$$

The missed detection probability of cooperative spectrum sensing is given by

$$Q_{md}^K = \prod_{i=1}^{K} P_{md,i} = \prod_{i=1}^{K} (1 - P_{d,i}(\lambda_K, \gamma)) \tag{4}$$

where λ_K is the detection threshold with K SUs performing spectrum sensing.

III. Sensing Strategy with Selfish SUs

In this section we formulate cooperative spectrum sensing under the scenario with selfish SUs as a non-cooperative spectrum sensing game. We then analyze the mixed strategy Nash equilibrium of the formulated sensing game.

A. Spectrum Sensing Game

In this scenario we assume that SUs are selfish and rational with the aim of maximizing their utility. Hence we formulate the spectrum sensing game as a non-cooperative spectrum sensing game.

Definition 1. *The cooperative spectrum sensing game of interest is defined as follows:* $G = \langle N, \{s_i\}, \{\pi_i\} \rangle$.

- Players: there are N players with each player $i \in \{1, 2, \cdots, N\}$
- Actions: each player may choose to sense or not to sense. The action of player i is denoted by $s_i \in \{0, 1\}$. $s_i = 0$ indicates not performing sensing while $s_i = 1$ means sensing the channel.
- Payoff function: the expected payoff for SU i is given by

$$\pi(p_i, p_{-i}) = p_i \cdot U_s + (1 - p_i) \cdot U_n \tag{5}$$

  where SU i performs spectrum sensing with the probability of p_i and no spectrum sensing with the probability of $1 - p_i$. $p_{-i} = (p_1, \cdots, p_{i-1,} p_{i+1}, \cdots p_N)$ denotes the sensing probabilities of all the players except play i. U_s and U_n are the expected utilities of a SU performing sensing or not respectively. The utility function derivation is shown in Section III B.

For a given strategy profile p_{-i} of all the players except player i, player i wants to maximize its expected payoff by choosing the best sensing strategy to cooperate with other SUs while guaranteeing the missed detection probability below a given threshold. Therefore, the optimization problem can be formulated as follows.

$$Max \quad \pi(p_i, p_{-i}) = p_i \cdot U_s + (1 - p_i) \cdot U_n \tag{6}$$

Under the constraints of

$$0 \le p_i \le 1$$

$$Q_{md}^K \le Q_{th} \quad (K = 1, 2, \cdots, N)$$

where K is the number of SUs performing spectrum sensing and Q_{th} is the threshold of detection probability imposed by PUs.

B. Utility Function Derivation

1) Average False Alarm Probability: Denote $P = (p_1, p_2, \cdots, p_N)$ as the sensing probability vector of SUs. For a given time slot the strategies of SUs can be represented as $S = (s_1, s_2, \cdots, s_N)$ and assume that there are $K\,(0 \le K \le N)$ SUs performing spectrum sensing.

If SU i chooses to sense the channel, which means the channel will be sensed by at least one SU, then $1 \le K \le N$ holds. In such a case there are $r_{K,S} = \binom{N-1}{K-1}$ combinations where K out of N SUs are performing spectrum sensing. The probability of each combination can be calculated by $\prod_{n=1;n\neq i}^{N} p_n^{s_n}(1 - p_n)^{1-s_n}$. Hence the probability of K SUs (including SU i) cooperating to sense the channel is given by

$$q_S^K = \sum_{j=1}^{r_{K,S}} \prod_{n=1;n\neq i}^{N} p_n^{s_n}(1 - p_n)^{1-s_n} \tag{7}$$

If SU i chooses not to sense the channel, which means that $0 \le K \le N-1$ holds. In such a case there are $r_{K,N} = \binom{N-1}{K}$ combinations where K out of N SUs are performing spectrum sensing. Hence the probability of K SUs (excluding SU i) cooperating to sense the channel is given by

$$q_N^K = \sum_{j=1}^{r_{K,N}} \prod_{n=1;n\neq i}^{N} p_n^{s_n}(1 - p_n)^{1-s_n} \tag{8}$$

In CRNs it is very important to efficiently identify the potential spectrum opportunities while protecting PUs from harmful interference. Hence the missed detection probability has to be kept below a given threshold. It has been shown in [5][6] that the minimum false alarm probability can be achieved when the inequality of the constraint reaches the threshold of the detection probability. Hence for a given number, k, of SUs performing spectrum sensing, the optimal detection threshold for collaborative SUs can be optimized such that the minimum false alarm probability, Q_f^k, can be achieved. It is also obvious that $Q_f^1 > Q_f^2 > \cdots > Q_f^N$ holds.

Therefore if SU i chooses to sense the channel, then the average false alarm probability is given by

$$\bar{Q}_{fs} = \sum_{n=1}^{N} q_S^n \cdot Q_f^n \tag{9}$$

If SU i chooses not to sense the channel and the channel is sensed, then the average false alarm probability is given by

$$\bar{Q}_{fn} = \sum_{n=1}^{N-1} q_N^n \cdot Q_f^n \Big/ (1 - \Lambda) \tag{10}$$

where $\Lambda = \prod_{n=1;n\neq i}^{N} (1 - p_n)$ represents the probability that none of SUs senses the channel.

2) Calculation of Expected Utility: It is assumed that a successful transmission of SUs achieves the throughput of C_t while performing spectrum sensing once incurs sensing cost C_c. No spectrum sensing by SUs causes the penalty of spectrum waste C_p. Unsuccessful transmissions under missed detections result in no SU throughput due to collisions between SUs and PUs. The relationships of the strategies and rewards are shown in TABLE I.

Denote P_r as the channel availability for SUs. If SU i chooses to sense the channel, the expected utility is given by

$$\begin{aligned} U_s(p_{-i}) &= (C_t - C_c) \cdot P_r \cdot \left(1 - \bar{Q}_{fs}\right) + \\ &\quad (-C_c) \cdot \left((1 - P_r) + P_r \bar{Q}_{fs}\right) \\ &= C_t \cdot P_r \cdot \left(1 - \bar{Q}_{fs}\right) - C_c \end{aligned} \tag{11}$$

TABLE I
STRATEGIES AND REWARDS

Rewards	Sense	Not Sense
Successful Transmission	$C_t - C_c$	C_t
Unsuccessful Transmission	$-C_c$	0
None of SUs sensing	N/A	$-C_p$

If SU i chooses not to sense the channel, the expected utility is given by

$$U_n(p_{-i}) = C_t \cdot (1-\Lambda) \cdot P_r \cdot \left(1-\bar{Q}_{fn}\right) + \Lambda \cdot P_r \cdot (-C_p) \quad (12)$$

C. Nash Equilibrium Analysis

As at the beginning of each time slot each SU makes its move simultaneously and has an independent sensing strategy, in general a SU will decide to play each of these strategies with some probabilities. In game theory, the mixed strategy is used to represent the probability distribution of a player over his pure strategies. In this paper we focus on the mixed-strategy Nash equilibrium as SUs may randomize their strategies in order to maximize their utility while the dynamics of the spectrum sensing game will be left for our future work. Hence we have the following theorem.

Theorem 1. *The formulated spectrum sensing game has a mixed strategy Nash equilibrium.*

Proof: In the formulated spectrum sensing game, each player has two different strategies, so there are finite strategies for the formulated game for a given number of SUs in the network. According to the theorem in [14] that every finite strategic game has a mixed strategy Nash equilibrium, Theorem 1 holds true. ■

For a given strategy profile of all other players p_{-i}, in order to obtain the best response for SU i, we examine the first order derivative of the utility function with respect to p_i given by,

$$\begin{aligned}\frac{\partial \pi(p_i,p_{-i})}{\partial p_i} &= U_s(p_{-i}) - U_n(p_{-i}) \\ &= C_t \cdot P_r \cdot \left(1-\bar{Q}_{fs}\right) - C_c - \Lambda \cdot P_r \cdot (-C_p) \\ &\quad - C_t \cdot (1-\Lambda) \cdot P_r \cdot \left(1-\bar{Q}_{fn}\right) \\ &= \mathrm{A}_{-i}\end{aligned} \quad (13)$$

Hence, the best response of player i can be given as below:

$$S(p_{-i}) = \begin{cases} 1 & if \quad A_{-i} > 0 \\ any & if \quad A_{-i} = 0 \\ 0 & if \quad A_{-i} < 0 \end{cases} \quad (14)$$

In the mixed strategy Nash equilibrium none of the players can do better by unilaterally changing his strategy. Alternatively, a Nash equilibrium is a strategy profile comprised of mutual response of the players [14]. Hence for each SU i $A_{-i} = 0$ holds true. By combining all $A_{-i} = 0 \quad (i \in 1, 2, \cdots, N)$, we have N equations with the variable vector $P = (p_1, \cdots, p_{i,} \cdots, p_N)$. It is observed that all equations have the same expression with a different variable name, indicating that these variables have the same value, that is $p_1 = p_2 = \cdots = p_N = p$. In this case $U_s(p_{-i})$ is a function with regard to p, hence we use $U_s(p_{-i})$ and $U_s(p)$ interchangeably in the following. Similarly we use $U_n(p_{-i})$ and $U_n(p)$ interchangeably. Therefore finding the best strategy of a SU is equivalent to obtaining the solution of equation (15).

$$U_s(p) - U_n(p) = 0 \quad (15)$$

where p of interest is in the interval of $[0, 1]$.The above nonlinear equation can be easily solved by using the algorithm which is similar to the proposed algorithm in Section IV B.

IV. Sensing Strategy with Limited Collaboration

In this section we investigate the sensing strategy under the scenario with limited collaboration of SUs and formulate cooperative spectrum sensing as a nonlinear optimization problem.

A. Problem Formulation

In this scenario we assume that SUs perform spectrum sensing with limited collaboration, which means that rational SUs are willing to cooperate with each other and they have the same algorithms to decide their strategies. In other words, although each SU makes its own decision to sense or not, SUs are coordinated with the limited information of the network, such as channel availability and the number of SUs in the CRN.

It is observed that under the limited collaboration SUs will be indifferent in terms of the sensing strategies when homogeneous SUs are considered, that is, $p_1 = p_2 = \cdots = p_N = p$ holds. The expected utility of a SU is computed by Equation (5), hence the optimization problem can be formulated as follows:

$$Max \quad \pi_c(p) = p \cdot U_s(p) + (1-p) \cdot U_n(p) \quad (16)$$

under the constraints of

$$0 \le p \le 1$$

$$Q_{md}^K \le Q_{th} \quad (K = 1, 2, \cdots, N)$$

where K is the number of SUs performing spectrum sensing and Q_{th} is the threshold of detection probability imposed by PUs. $U_s(p)$ and $U_n(p)$ can be calculated in the same approach as in Section III B.

B. The Proposed Algorithm

Under the scenario with limited collaboration among SUs, in order to find out the optimal sensing probabilities of SUs, we propose a Newton-Raphson-based algorithm.

As the formulae of the calculation on the expected utility of a SU shown in Equation (11)(12)(16) are ready, it is easy for us to obtain the first order derivative, denoted by $\pi_c'(p)$, which is given by

$$\pi_c'(p) = U_s(p) + p \cdot U_s'(p) - U_n(p) + (1-p) \cdot U_n'(p) \quad (17)$$

where $U_s'(p)$ and $U_n'(p)$ are the first order derivative of $U_s(p)$ and $U_n(p)$ respectively. Then we set

$$\pi_c'(p) = 0 \quad (18)$$

Algorithm 1 Optimal Sensing Probability

Require: $N = 200$, $p_0 = 0$, $eps = 1e - 5$
Ensure: Optimal sensing probability $p*$
  if $\pi_c'(p) > 0$ for any p $p \in [0, 1]$ **then**
    $p* \leftarrow 1$
  else if $\pi_c'(p) < 0$ for any p $p \in [0, 1]$ **then**
    $p* \leftarrow 0$
  else
    while $N > 0$ **do**
      $p_{n+1} \leftarrow p_n - \pi'_c(p_n)/\pi''_c(p_n)$
      if $abs(\pi_c'(p_{n+1})) < eps$ **then**
        $p* \leftarrow p_{n+1}$
        break
      else
        $N \leftarrow N - 1$
        $p_n \leftarrow p_{n+1}$
      end if
    end while
  end if

and aim to find out the root of Equation (18). For the cases of piratical interest where the throughput achieved by a successful transmission is far more than the cost performing spectrum sensing once, the expected utility of a SU should increase and then decrease when the sensing probabilities of SUs increase. In this case we can employ Newton-Raphson algorithm to obtain the root of Equation (18) since the second order derivative of the objective function, denoted by $\pi_c''(p)$, can be readily obtained. Hence we develop a Newton-Raphson based algorithm, shown in **Algorithm 1**, to obtain the optimal sensing probabilities of SUs.

V. Numerical Results

In this section we present numerical results and investigate the sensing strategies under different scenarios. In the following, we assume that C_t is equal to 1 unit and define $\alpha = C_c/C_t$ to represent the sensing cost and $\beta = C_p/C_t$ as the penalty of no sensing by SUs. If not specified, the channel availability and β are set to be 0.7 and 1 respectively and 10 SUs are assumed in the network. The product of the spectrum sensing time and channel bandwidth is set to be 5 [2][3].

A. SU Expected Utility with Different Sensing Probability

In the simulation it is assumed that the average SNR values of the PU signal at each SU side are set to be 10dB, 8dB and 6dB respectively. α is set to be 0.2. The sensing probability of each SU is assumed to be the same.

Fig. 2 shows the expected utility of each SU when all SUs have the same sensing probabilities under different SNR values. It is observed that there exists an optimal probability of spectrum sensing under which a SU is able to maximize its utility. The expected utility of SUs first increases and then decreases when the sensing probability increases. This is because when the probability of performing sensing is very small, which means that most of the time only a very small number of SUs sense the channel, the false alarm probability is relatively high or even some penalties may incur. Thus increasing sensing probability of SUs significantly improves the sensing performance and the SU throughput improvement is dominant over the increase of the sensing cost, therefore the utility of a SU increases. After the utility reaches the peak point, it decreases gradually because further increasing the number of SU performing spectrum sensing obtains the insignificant improvement in sensing performance, but the sensing cost has a more significant impact on the utility. Moreover, SUs can achieve a higher utility when they have higher SNR values. This is because a higher SNR value indicates that SUs can achieve better sensing performance in terms of false alarm probability, thereby identifying more spectrum opportunities.

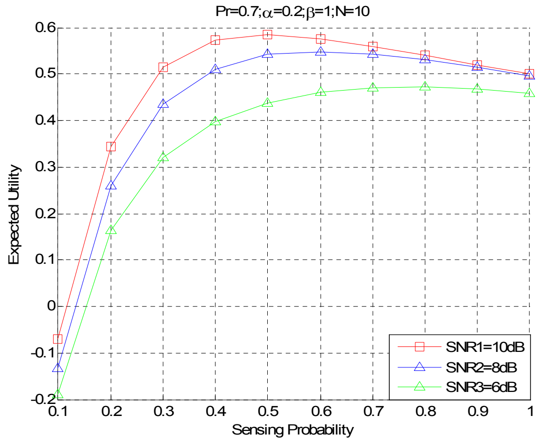

Fig. 2. The Expected Utility of A SU with Different Sensing Probability

B. Comparison of Strategy under Different Scenarios

In the simulation, we assumed that the average SNR values of the PU signal at each SU side is set to 10dB. α varies from 0 to 0.2. We denote "Nash" as the outcome of the Nash equilibrium under the scenario with selfish SUs (Scenario I) and "Optimal" as the outcome under the scenario with limited collaboration (Scenario II).

Fig. 3 and Fig. 4 show the sensing probability and the achieved utility under different scenarios while varying the sensing cost. For each scenario, it can be seen from the figures that when the sensing cost increases, SUs have less incentive to perform sensing, thereby decreasing their utility. For a given sensing cost, the sensing probability in Scenario II is higher than that in Scenario I, thus SUs might be able to significantly improve the sensing performance while the increase of the sensing cost has a minor impact on the utility, therefore SUs in Scenario II obtain higher utility than that of Scenario I. The comparisons between these two scenarios also demonstrate that the outcome of the Nash equilibrium is not optimal when nonzero sensing cost is considered and by limited collaboration SUs can achieve much better performance.

Fig. 5 shows the sensing probabilities of SUs under different channel availability and different number of SUs while fixing

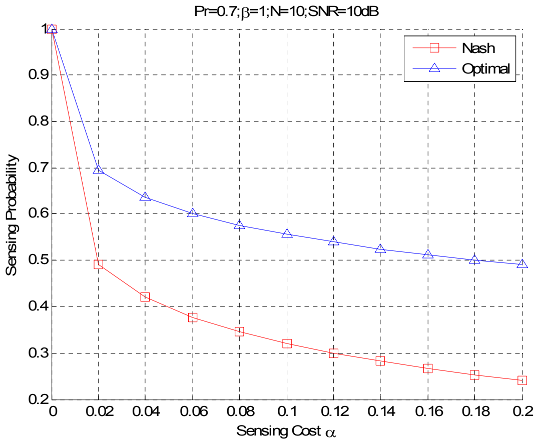

Fig. 3. Sensing Strategies of SUs under Different Scenarios

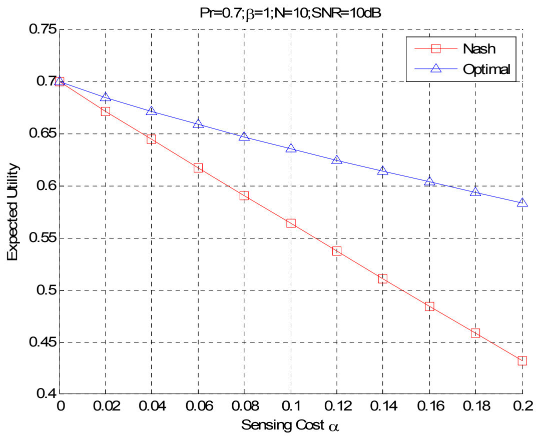

Fig. 4. The Expected Utility of A SU under Different Sensing Cost

the sensing cost and penalty. According to the figure, for a given number of SUs, when the channel availability increases, SUs tend to be more active in participating in spectrum sensing. This is because higher channel availability indicates more potential spectrum opportunities which can be identified by performing spectrum sensing. In addition, for a given channel availability, it is also shown that when the number of SUs is larger, the sensing probability of a SU decreases. The reason is that in order to achieve the same sensing performance, if there are more SUs being involved in spectrum sensing, SUs are more likely to rely on other SUs and perform spectrum sensing less frequently.

VI. Conclusion

In this paper, we presented a cooperative spectrum sensing model with consideration to the spectrum sensing cost in distributed CRNs. We then investigated the sensing strategies of SUs under two different scenarios. Under the scenario with selfish SUs, we formulated cooperative spectrum sensing as a non-cooperative game and obtained the sensing probabilities by analyzing the mixed strategy Nash equilibrium. Under the scenario of limited collaboration, we formulated it as a nonlinear optimization problem and derived the optimal

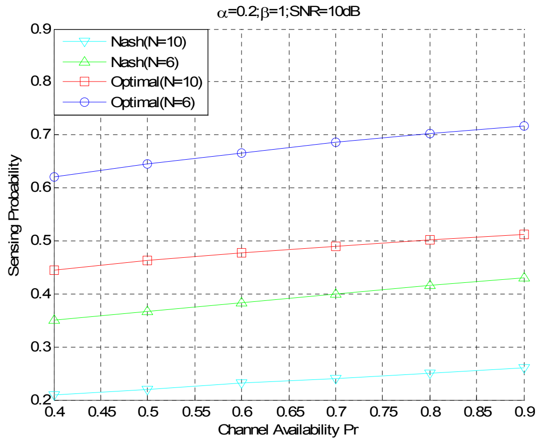

Fig. 5. Sensing Probabilities under Different Channel Availability and the Number of SUs

sensing strategies of SUs. Numerical results show that SUs under limited collaboration are able to achieve much better performance than the outcome of the Nash equilibrium and by choosing the optimal sensing strategy SUs are able to make an effective tradeoff between SU throughput and sensing cost.

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