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Optimal Cooperative Sensing Assignment and Radio Resource Allocations for Cognitive Radio Systems

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Abstract: This study investigates the joint sensing assignment and resource allocations for Cognitive Radio (CR) systems where multiple Secondary Users (SUs) opportunistically share the channels of Primary System (PS) through cooperative sensing. The key questions concerned here are how to assign different SUs to sense different channels and how to allocate the transmission power and bandwidth for SUs such that the detected idle channels of PS are fully utilized. Specifically, the cooperative spectrum sensing improves the detection accuracy and reduces the potential interference to PS due to mis-detection. However, the cooperative spectrum sensing and the consequent reports of sensing results consume additional energy which should be taken account of in the SU resource allocations. Hence, the coupling effect between the spectrum sensing and the consequent resource allocations is critical for CR to optimize its performance. Based on these considerations, the problem of joint sensing assignment and resource allocations for CR is formulated as a mixed binary nonlinear programming problem and a two-layer procedure is proposed to obtain the optimal solutions. The extensive results show that due to the energy overhead for sensing and reporting, the optimal number of SUs assigned to sense the PU channel does not increase in the idle probability of the channel monotonically. Meanwhile, to maximize the SUs throughput, the consequent optimal transmission power and bandwidth allocations heavily depend on the sensing accuracy determined by the optimal sensing assignment.

Key words: Cognitive radio network, cooperative sensing, sensing assignment, bandwidth and power allocations

INTRODUCTION

Cognitive Radio (CR), capable of detecting and making use of idle spectrum resource intelligently and flexibly, has been considered as an efficient approach to improve the spectrum utilization (Haykin, 2005). A key functionality of CR is its spectrum sensing based on which the CR-user (also termed as the Secondary User, SU) detects the idle spectrum left by Primary System (PS). Hence, an accurate spectrum sensing (including both the detection probability and the false alarm probability) plays an important role to the performance of CR. Conventional techniques for spectrum sensing include energy-detection, feature-detection and matched filtering and coherent detection (Wang and Liu, 2011; Zhao *et al.*, 2010; Cai *et al.*, 2011). To further improve the sensing accuracy, cooperative sensing has been proposed, where several SUs are organized to sense the same channel (Fan and Jiang, 2010). However, different from traditional wireless systems, cooperative spectrum sensing and the consequent procedure of reporting sensing results consume additional system-overheads. Hence, the tradeoff between the system resources consumed for spectrum sensing and those for effective data transmission for CR attracts lots of research interests (Stotas and Nallanathan, 2011; Peh *et al.*, 2009, 2011; Fan *et al.*, 2011; Yucek and Arslan, 2009; Zhang *et al.*, 2008). For example, the authors of (Peh *et al.*, 2011) investigated the optimization of sensing time and power allocation to improve the average data rate and outage probability. Fan *et al.* (2011) discussed how to set spectrum-sensing time and threshold and how to allocate spectrum resources consequently. Besides the time-overheads considered by Peh *et al.* (2011) and Fan *et al.* (2011), the spectrum sensing and the report of sensing result also incur additional energy consumption which should be taken account of in the SU consequent transmission power allocation. Thus, the coupling effect

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between the cooperative spectrum sensing and the consequent transmission resource allocation motivates this study to investigate the following questions, namely, how to jointly assign different SUs to sense different channels and in further how to allocate the transmission power and bandwidth for the SUs based on the resulting sensing accuracy such that the overall performance (e.g., throughput) of SUs can be optimized (Liang *et al*., 2011). Specifically, this study firstly formulates the aforementioned problem as a mixed binary nonlinear programming problem and then proposes a two-layer procedure to obtain the optimal solutions. The numerical results show that due to the energy overhead for sensing and reporting, the optimal number of SUs assigned to sense the PU channel does not increase in the idle probability of the channel monotonically. Meanwhile, to maximize the SUs throughput, the consequent optimal transmission power and bandwidth allocations heavily depend on the sensing accuracy which is determined by the optimal sensing assignment.

SYSTEM MODEL

Network model: The study considers a PS consisting of a group of K licensed channels (denoted by K = {1, 2,..., K}). Meanwhile, a group of SU transceiver pairs (denoted by N = {1, 2,..., K}) opportunistically access the PU channels via the sensing-based overlay model (Liang *et al*., 2011) and each SU pair consists of an SU transmitter (SUTx) and an SU receiver (SURx). The SUs are assumed to synchronize with the PS and operate based on a frame-by-frame structure. Specifically, each frame is divided into three parts with fixed durations, namely, a sub-slot for cooperative spectrum sensing, a sub-slot for reporting the sensing results and a sub-slot for data transmission.

Model of cooperative spectrum sensing: Assume that the SUs utilize the cooperative spectrum sensing to improve the sensing accuracy. Specifically, within the sub-slot for spectrum sensing, the CR base station assigns different number of SUs to sense different PU channels. Let $a_n^k = 1$ ($a_n^k = 0$) denote that the SU n is (is not) assigned to sense the PU channel k. As a practical assumption, each individual SU is able to achieve the same sensing accuracy measured by the detection probability $p_{de} = \Pr\{\tilde{s}^k = 0|s^k = 0\}$ and the false alarm probability $p_{fa} = \Pr\{\tilde{s}^k = 0|s^k = 1\}$, respectively which are homogenous among all the PU channels.

Followed by the sub-slot for spectrum sensing, in the sub-slot for reporting, each SU sends its sensing result to the CR base station which further determines the availability of the PU channel. Suppose that the base station uses the OR-rule to combine the sensing results from all SUs assigned to sense the same channel. In other words, instead of using the soft-decision, we adopt the hard-decision for decision-fusion which saves the bandwidth for reporting (Yucek and Arslan, 2009). Then the detection probability for the PU channel k can be given by:

$$\hat{p}_{de}^{k}\left(\sum_{n=1}^{N} a_n^k\right) = 1-(1-p_{de})^{\sum_{n=1}^{N} a_n^k} \tag{1}$$

where, $\sum_{n=1}^{N} a_n^k$ denotes the total number of SUs assigned to sense the channel k. Meanwhile, the corresponding false alarm probability for the PU channel k can be given by:

$$\hat{p}_{fa}{}^{k}\left(\sum_{n=1}^{N} a_n^k\right) = 1-(1-p_{fa})^{\sum_{n=1}^{N} a_n^k} \tag{2}$$

Model of resource allocations and SUs throughput: Based on the combined sensing result for each PU channel, the CR base station determines the status of the PU channel. Specifically, if the PU channel k is determined to be idle, then CR allocates the bandwidth of channel k to SUs for data transmission as well as the corresponding transmission power. Let p_n^k denote the transmission power for the SU n over channel k and let λ_n^k denote the share of the transmission bandwidth for the SU n over channel k. Assume that SUs can orthogonally share the idle channels of PS, e.g., through the Orthogonal Frequency Division Multiplexing Access (OFDMA) (similar assumption also appeared (Fan *et al*., 2011; Li *et al*., 2011). Specifically, due to the sensing error, there exist two different cases (i.e., case 1 and 2) when the SUs detects the channel is idle.

Case 1: The sensing result on channel k shows that the PU is idle. However, the PU true state is busy, i.e., a mis-detection happens. Based on the above Eq. 1, the probability for Case 1 to happen is given by:

$$\theta_{01}^{k} = \pi_0^k\left(1-\hat{p}_{de}\left(\sum_{n=1}^{N} a_n^k\right)\right) \tag{3}$$

Meanwhile, in this case, the achievable throughput on channel k can be measured by:

$$r_0^k = \sum_{n=1}^{N} \lambda_n^k B^k \log_2\left(1+\frac{p_n^k g_{ssn}{}^{k}}{\lambda_n^k (Y g_{ps}{}^{k} + n_0 B^k)}\right) \tag{4}$$

Specifically, $g^{k}{}_{ssn}$, $g^{k}{}_{spn}$ and $g^{k}{}_{psn}$ denote the channel power gains of the nth secondary link between SU-Tx and SU-Rx, the link between nth SU-Tx and PU-Rx and the link between PU-Tx and nth SU-Rx, respectively. Y denotes the transmission power of PU in the channel. B^k denotes the bandwidth of channel k. n_0 is power density of the background noise.

Case 2: The sensing result on channel k shows that the PU is idle and the PU true state is idle, i.e., no false alarm happens. Based on Eq. 2, the probability for Case 2 to happen is given by:

$$\theta_{11}^k = \pi_1^k \left(1 - \hat{p}_{fa}\left(\sum_{n=1}^{N} a_n^k\right)\right) \tag{5}$$

Meanwhile, in this case, the achievable throughput on channel k can be measured by:

$$r_1^k = \sum_{n=1}^{N} \lambda_n^k B^k \log_2\left(1 + \frac{p_n^k g_{ssn}{}^k}{n_0 \lambda_n^k B^k}\right) \tag{6}$$

Based on the two different cases described above, the average throughput of the PU channel k can be given by:

$$R^k = \theta_{01}^k r_0^k + \theta_{11}^k r_1^k \tag{7}$$

where, $\theta^k_{ij} = \Pr\{\tilde{s}^k = j, s^k = i\}$ denotes the joint probability that the PU true state is $s^k = i$ and the SU sensing result is $\tilde{s}^k = j$. In summary, the average throughput of all SUs can be given by:

$$R^{total} = \sum_{k=1}^{K} R^k = \sum_{k=1}^{K} \left[\begin{array}{l} \theta_{01}^k \sum_{n=1}^{N} \lambda_n^k B^k \log_2\left(1 + \dfrac{p_n^k g_{ssn}{}^k}{\lambda_n^k (Y g_{psn}{}^k + n_0 B^k)}\right) \\ + \theta_{11}^k \sum_{n=1}^{N} \lambda_n^k B^k \log_2\left(1 + \dfrac{p_n^k g_{ssn}{}^k}{\lambda_n^k n_0 B^k}\right) \end{array} \right] \tag{8}$$

Model of constraints for resource allocations: An important issue of the CR system is to protect the PS from harmful interference. Firstly, the occurrence of mis-detection should be limited which is denoted by the following constraint:

$$p_{md}^k\left(\sum_{n=1}^{N} a_n^k\right) = 1 - \hat{p}_{de}\left(\sum_{n=1}^{N} a_n^k\right) \le \xi^k \tag{9}$$

Specifically, ξ^k denotes the tolerable threshold for misdetection probability. It is worth emphasizing that constraint (9) alone may not be enough for incumbent protection since the SU power also plays an important role in causing interference to the PS. Hence, to further limit the average interference suffered by the PS on channel k, the following constraint is adopted:

$$\sum_{n=1}^{N} \theta_{01}^k p_n^k g_{spn}{}^k \le I_{th}^k \tag{10}$$

where, I^k_{th} denotes the threshold for tolerable interference in channel k.

As mentioned before, besides the transmission power, the cooperative spectrum sensing and the consequent report of sensing result also consume additional energy. Let $q_{s,n}$ denote the power consumption spent for spectrum sensing and let $q_{r,n}$ denote the transmission power to guarantee a successful report of sensing result, respectively. Notice that both $q_{s,n}$ and $q_{r,n}$ depend on the selection of SU n. In particular, the average total energy consumption for SU n should be limited below a threshold P_n^{ave}. Therefore, the constraint of the average total energy consumption for SU n can be given by:

$$\sum_{k=1}^{K} [a_n^k (q_{s,n} + q_{r,n}) + (\theta_{01}^k + \theta_{11}^k) p_n^k] \le p_n^{ave}, \forall n \tag{11}$$

In addition, the instantaneous transmission power for each SU is also limited and this constraint is given by:

$$\sum_{k=1}^{K} p_n^k \le p_n^{peak} \tag{12}$$

where, P_n^{peak} is the upper bound for instantaneous transmission power determined by the SU transceiver.

PROBLEM FORMULATION

As mentioned earlier, this study considers a joint sensing assignment and resource allocations (including both the transmission power and the bandwidth allocation) problem which aims at maximizing the average throughput of all SUs as follows:

$$\text{Problem P1:} \max_{\{a_n^k\},\{p_n^k\},\{\lambda_n^k\}} R^{total} \tag{13}$$

$$\text{Subject to:} \sum_{n=1}^{N} \lambda_n^k \le 1, \forall k \tag{13a}$$

$$1 - \hat{p}_{de}{}^k\left(\sum_{n=1}^{N} a_n^k\right) \le \xi^k, \forall k \tag{13b}$$

$$\sum_{k=1}^{K} a_n^k \le 1, a_n^k \in \{0,1\}, \forall n \tag{13c}$$

$$\sum_{k=1}^{K} p_n^k \le p_n^{peak}, \forall n \tag{13d}$$

$$\sum_{k=1}^{K} [a_n^k (q_{s,n} + q_{r,n}) + (\theta_{01}^k + \theta_{11}^k) p_n^k] \le p_n^{ave}, \forall n \tag{13e}$$

$$\sum_{n=1}^{N} \theta_{01}^k p_n^k g_{spn}{}^k \le I_{th}^k, \forall k \tag{13f}$$

Notice that R^{total} is given by Eq. 8. Problem (P1) is a mixed binary nonlinear programming problem which is difficult to solve in general. Thus, we first use the GAMS, a commercial optimization software (http://www.gams.com/docs/document.htm), to obtain the optimal sensing assignment and the corresponding optimal resource allocations. In addition, the study also proposes a two-layer optimization framework, including a lower-layer and an upper-layer, to solve problem (P1) by exploiting its special structure. Specifically, in the lower-layer of this framework, all the SUs aim at determining the transmission power and bandwidth allocations based on the given spectrum sensing assignment. Further in the upper-layer of this framework, the CR system determines the spectrum sensing assignment based on the optimized resource allocations from the lower-layer. The details are illustrated as follows:

- **The lower-layer problem:** It gives the cooperative spectrum sensing assignment $\{a_n{}^k\}$, all SUs determine their power allocations $\{p_n{}^k\}$ and bandwidth allocations $\{\lambda_n{}^k\}$ by solving the following problem:

$$\text{Problem P2:} \max_{\{p_n^k\},\{\lambda_n^k\}} R^{total} \tag{14}$$

$$\text{Subject to:} \sum_{n=1}^{N} \lambda_n^k \le 1, \forall k \tag{14a}$$

$$\sum_{k=1}^{K} p_n^k \le p_n^{peak}, \forall n \tag{14b}$$

$$\sum_{k=1}^{K} [a_n^k (q_{s,n} + q_{r,n}) + (\theta_{01}^k + \theta_{11}^k) p_n^k] \le p_n^{ave}, \forall n \tag{14c}$$

$$\sum_{n=1}^{N} \theta_{01}^k p_n^k g_{spn}{}^k \le I_{th}^k, \forall k \tag{14d}$$

Notice that when the sensing assignment $\{a_n{}^k\}$ is given, the lower-layer problem (P2) is in fact a convex optimization problem (Wu and Tsang, 2011; Boyd and Vandenberghe, 2004). Therefore, problem (P2) can be solved efficiently, e.g., by using interior point method. Further let $\{\tilde{p}_n{}^k\}$ and $\{\tilde{\lambda}_n{}^k\}$ denote the optimal transmission power and bandwidth allocations for problem (P2), respectively. It is apparent that $\{\tilde{p}_n{}^k\}$ and $\{\tilde{\lambda}_n{}^k\}$ depend on $\{a_n{}^k\}$ which hence can be explicitly denoted by $\{\tilde{p}_n{}^k(\{a_n{}^k\})\}$ and $\{\tilde{\lambda}_n{}^k(\{a_n{}^k\})\}$.

- **The upper-layer problem:** It gives the resulting transmission power $\{\tilde{p}_n{}^k(\{a_n{}^k\})\}$ and bandwidth allocation $\{\tilde{\lambda}_n{}^k(\{a_n{}^k\})\}$ from (P2), all the SUs further determines its cooperative sensing assignment by solving the following problem:

$$\text{Problem P3:} \max_{\{a_n^k\}} \tilde{R}^{total} \tag{15}$$

$$\text{Subject to: } 1 - \hat{p}_{de}{}^k\left(\sum_{n=1}^{N} a_n^k\right) \le \xi^k, \forall k \tag{15a}$$

$$\sum_{k=1}^{K} a_n^k \le 1, a_n^k \in \{0,1\}, \forall n \tag{15b}$$

$$\sum_{k=1}^{K} [a_n^k (q_{s,n} + q_{r,n}) + (\theta_{01}^k + \theta_{11}^k) p_n^k] \le p_n^{ave}, \forall n \tag{15c}$$

$$\sum_{n=1}^{N} \theta_{01}^k p_n^k g_{spn}{}^k \le I_{th}^k, \forall k \tag{15d}$$

Specifically, the objective function $\tilde{R}^{total}$ is given by:

$$\sum_{k=1}^{K}\left[\theta_{01}^k \sum_{n=1}^{N} \tilde{\lambda}_n^k(\{a_n^k\}) B^k \log_2\left(1 + \frac{\tilde{p}_n^k(\{a_n^k\}) g_{ssn}{}^k}{\tilde{\lambda}_n^k(\{a_n^k\})(\Upsilon g_{psn}{}^k + n_0 B^k)}\right) + \theta_{11}^k \sum_{n=1}^{N} \tilde{\lambda}_n^k(\{a_n^k\}) B^k \log_2\left(1 + \frac{\tilde{p}_n^k(\{a_n^k\}) g_{ssn}{}^k}{\tilde{\lambda}_n^k(\{a_n^k\}) n_0 B^k}\right)\right] \tag{16}$$

Notice that despite its simple form as a binary programming problem, the upper-layer problem (P3) is extremely difficult to solve since no analytical form for $\{\tilde{p}_n{}^k(\{a_n{}^k\})\}$ and $\{\tilde{\lambda}_n{}^k(\{a_n{}^k\})\}$ can be obtained yet. In this study, considering a moderate size of CR network, enumeration method is adopted to determine the optimal cooperative sensing assignment for problem (P3), whose computational complexity is measured by $O((K+1)^N)$. Nevertheless, the future work of this study is to design an efficient algorithm (e.g., by using the particle swarm algorithm (Kennedy and Eberhart, 1995; Gao *et al*., 2011) for large-size cognitive radio networks.

SIMULATION RESULTS

This section presents numerical results to show the obtained optimal sensing-assignment and resource allocations. Specifically, we consider a PS with 2 PU channels (each with a unit bandwidth) and a CR network with 4 SUs. The tolerable threshold for mis-detection on

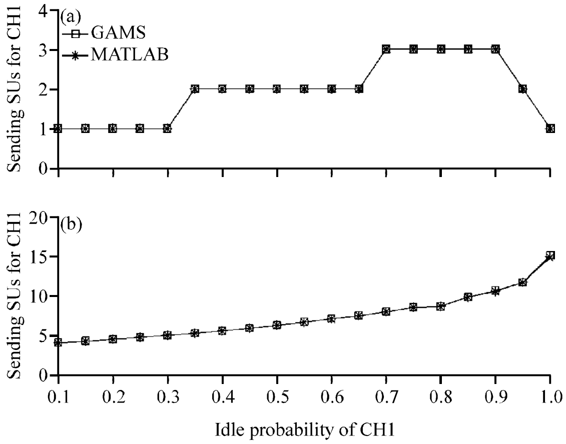

Fig. 1(a-b): (a) Optimal number of SUs assigned for the PU channel and (b) Optimal throughput of all SUs

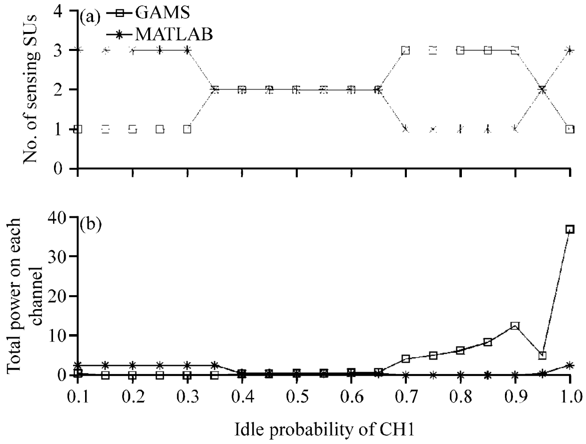

Fig. 2(a-b): (a) Optimal number of SUs assigned for sensing on each channel and (b) Optimal total transmission power allocation of all SUs on each channel

each channel k is given by $\xi^k = 0.3$. Meanwhile, for each SU, its detection probability $p_{de} = 0.8$ and its false alarm probability $p_{fa} = 0.1$ (in other words, to guarantee the required misdetection on each PU channel, at least one SU has to be assigned for each PU channel). In addition, the tolerable interference threshold for PU is $I^k_{th} = 0.001$ and the power of background noise is $n_0 = 0.001$. For a clear presentation, in this numerical simulation, we fix the stationary idle probability of PU channel 2 as $\pi_1^2 = 0.5$ and change the stationary idle probability of PU channel 1, i.e., π^1_1 from 0.10 to 1.00 with the granularity of 0.05. Our objective is to evaluate the impact of the idle probability of the PU channel.

Figure 1 shows the optimal sensing assignment for PU channel 1 (Fig. 1a) and the optimal total throughput (Fig. 1b) achieved by the proposed two-layer procedure. These results are consistent with those from GAMS very well, thus validating our proposed two-layer procedure.

Figure 2 plots the optimal number of SUs assigned to sense each PU channel and the transmission power allocations in each channel according to the sensing assignment. Surprisingly, the results show that the optimal number of SUs assigned to PU channel 1 does not increase monotonically with the idle probability of channel 1. Specifically, when π^1_1 increases from 0.1 to 0.90 roughly, the number of assigned SUs increases accordingly. This result is consistent with the intuition, since with the increase of idle probability of channel 1, it becomes more beneficial for the SUs to use channel 1 aggressively. Thus, via considering the interference constraint (13f), the SUs have to reduce the mis-detection probability on channel 1 such that they are allowed to use larger transmission power to fully utilize channel 1 when it is detected to be idle. As a result, the optimal number of SUs assigned to sense channel 1 increases. The transmission power allocation shown in Fig. 2b further verifies that the total transmission power of all SUs on channel 1 increases when π^1_1 increases from 0.1 to 0.90. Meanwhile, Fig. 6a verifies the interference constraint (13f) is always binding.

However, when the stationary idle probability π^1_1 increases from 0.90 to 1, the number of SUs assigned to sense channel 1 decreases. Intuitively, with the increase of the transmission power of SUs, the power capacity constraint (13e) becomes more stringent and the effect of energy-overhead for sensing and reporting becomes significant, indicating that it is not beneficial for SUs to keep such a high detection probability any more. Therefore, the total number of SUs assigned to sense channel 1 decreases. To verify this finding, we further detail the numerical results when π^1_1 increases from 0.90 to 1 using the granularity of 0.01. Figure 3a clearly shows that the total number of SUs assigned to sense channel 1 decreases and Fig. 3b further plots the total transmission power allocation on channel 1.

Figure 4 plots the total average power consumption of each SU (in comparison with its power capacity). Notice that the results shown in Fig. 2-4 illustrate how the optimal sensing assignment and the following transmission power allocation are strongly coupled

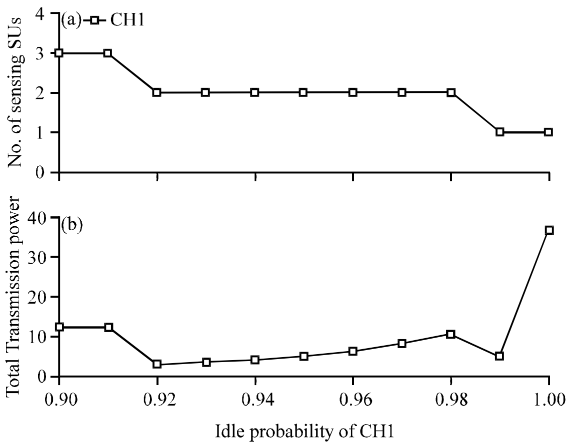

Fig. 3(a-b): (a) Optimal number of SUs assigned to sense channel 1 and (b) Optimal total transmission power allocation of all SUs on channel 1

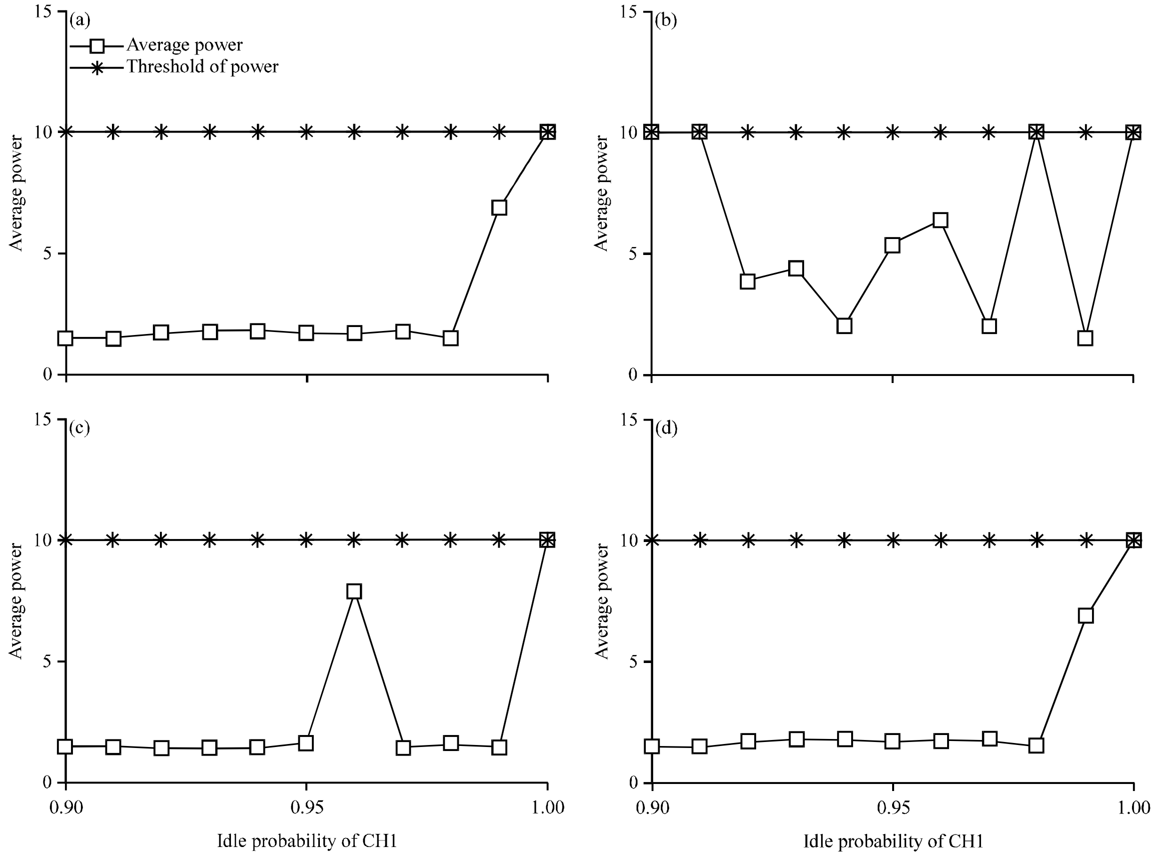

Fig. 4(a-d): Average power consumption of (a) SU1, (b) SU2, (c) SU3 and (d) SU4

together. Specifically, when the SUs' transmission power increase, the power capacity constraint for SU(s) becomes stringent (Fig. 4) until reaching the corresponding power capacity (around $\pi^1_1 = 0.91$). After that, the total number of SUs assigned to sense channel 1 decreases (Fig. 3) which resulting in a sudden increase of the mis-detection probability. Consequently, as shown in the top subplot of Fig. 6, to guarantee the interference to PUs below the

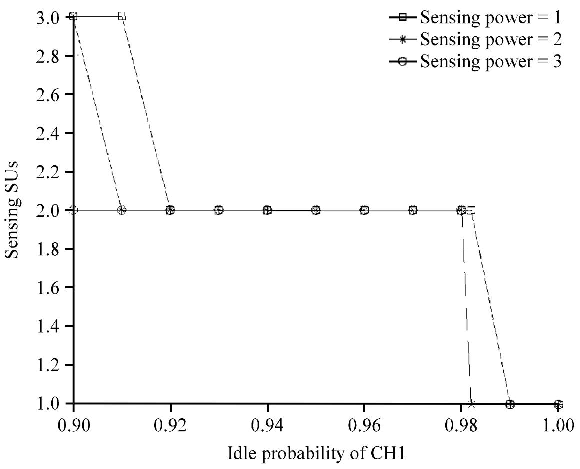

Fig. 5: Optimal sensing assignment with different power consumption required for spectrum sensing

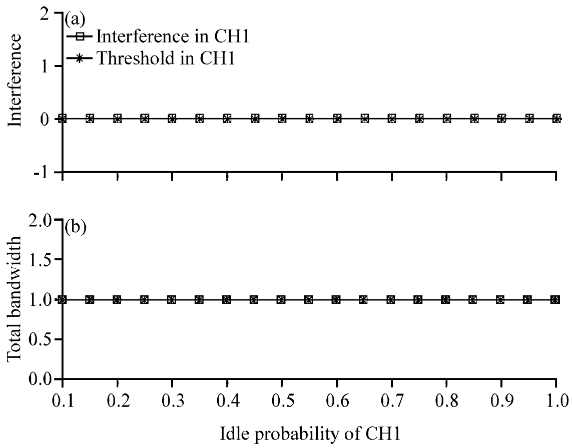

Fig. 6(a-b): (a) Total interference measured on PU channel 1 and (b) Total bandwidth consumption on channel 1

interference threshold, the total transmission power allocation of SUs on channel 1 decreases (Fig. 3) and so does the transmission power allocation of some SUs (i.e., SU 2 Fig. 4). After that, the transmission power of SU(s) increases gradually until the average power capacity constraint of SU(s) becomes binding and once again, the aforementioned phenomenon appears when $\pi^1_1 = 0.98$.

Figure 5 further evaluates the impact of the power consumption for spectrum sensing on the optimal number of SUs assigned to sense the PU channel 1. Apparently, as the power consumption for spectrum sensing increases, the optimal number of assigned SUs decreases, especially when the power capacity constraint becomes stringent. Meanwhile, Fig. 6b verifies that to maximize the total throughput, the bandwidth of each channel is always fully utilized when it is detected to be idle.

Figure 7 shows that the optimal bandwidth allocation for each SU always shares a similar trend as its optimal transmission power allocation. Specifically, each subfigure plots: (1) each SU's share of the total bandwidth (marked with star) and (2) the ratio between its transmission power over channel 1 and the aggregate transmission power of all SUs (marked with circle) over channel 1. Apparently, the optimal transmission power and bandwidth allocations are positively coupled together to maximize the throughput of all SUs.

Finally, Fig. 8 shows that as the idle probability of PU channel increases, the total throughput of all SUs increases based on the optimal sensing assignment and the corresponding transmission power and bandwidth

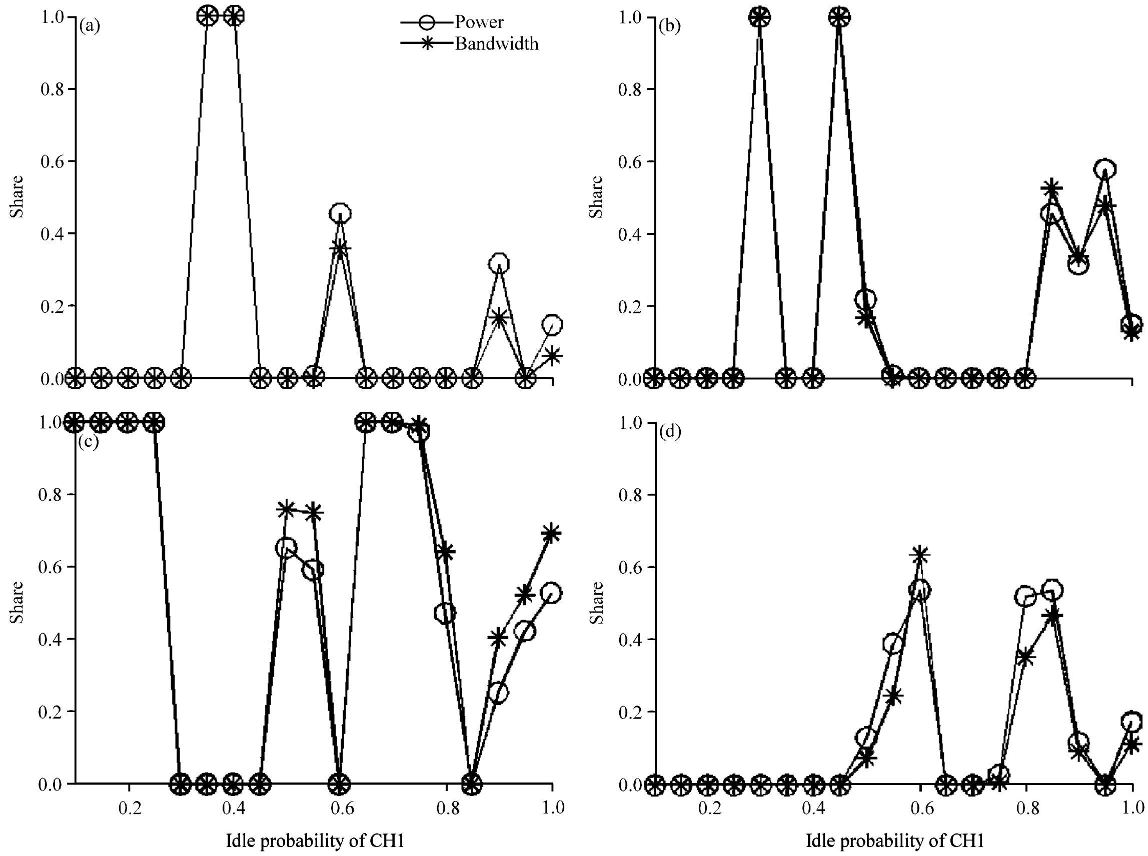

Fig. 7(a-d): Ratios of transmission power and bandwidth allocations for (a) SU1, (b) SU2, (c) SU3 and (d) SU4

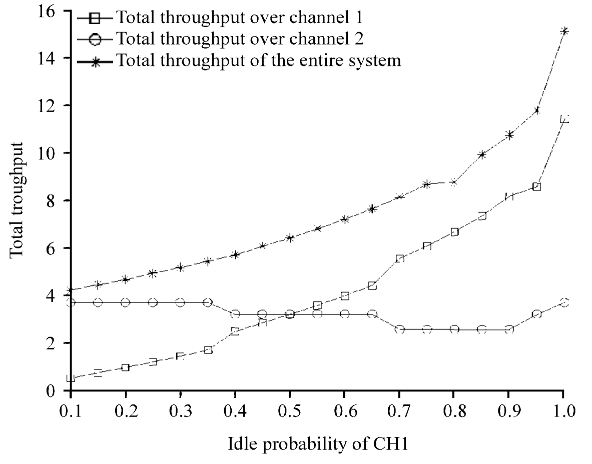

Fig. 8: Optimal throughput of all SUs

allocations obtained from our model. This result matches the intuition well since a larger idle probability channel always yields a great total throughput for CR by using the optimal spectrum sensing, transmission power and bandwidth allocations.

CONCLUSION

This study investigates the joint sensing assignment and resource allocations for cognitive radio systems which aim at maximizing the average throughput for all SUs. This study firstly formulates this concerned problem as a mixed binary nonlinear programming and then proposes a two-layer procedure to obtain the optimal solutions. The numerical results show the coupling effect between the optimal sensing assignment and the consequent transmission power and bandwidth allocations. Specifically, due to the energy overhead for spectrum sensing and reporting, the optimal number of SUs assigned to sense the PU channel does not monotonically increase in the idle probability of the channel. Furthermore, to maximize the SUs throughput, the consequently optimal transmission power and bandwidth allocations heavily depend on the sensing accuracy which is determined by the optimal sensing assignment.

As mentioned earlier, the computational complexity of the proposed two-layer procedure grows exponentially with the number of the PU channels which limits its usage in large scale networks. Thus, the future work of this study is to design efficient algorithms, trading off the computational complexity with the optimality (e.g., by using the particle swarm algorithm (Kennedy and Eberhart, 1995; Gao *et al*., 2011), to solve the joint spectrum sensing and resource allocations problem.

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