Secondary User Selection in Cooperative Sensing Scheduling: A Spectrum Opportunity-Energy Tradeoff View

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Abstract. Cognitive Radio (CR) is regarded to be suitable for improving energy efficiency in wireless communications. In this paper we focus on the critical mechanism for practical implementation of the Cognitive Radio Networks (CRNs), i.e. cooperative sensing. Under the context of cooperative sensing, selecting more Secondary Users (SUs) for spectrum sensing can bring higher expected throughput, but more energy will be consumed on the sensing process, which is the major energy consumption in the CRNs. After selecting the SUs for sensing, how to properly assign them to sense the Primary User (PU) channels to strike the balance between sensing accuracy and spectrum opportunities is another essential problem. We formulate this two-dimensional Spectrum Opportunity-Energy Tradeoff (SOET) problem as a combinatorial optimization problem, and analytically exploit its inherent structures. Efficient algorithm is proposed to obtain the optimal solutions based on the properties found. Numerical results are also provided to validate our analysis.

Keywords: cognitive radio, cooperative sensing scheduling, opportunity-energy tradeoff, energy efficiency.

1 Introduction

The next generation wireless networks are expected to meet people's ever-growing demand of high speed access. However, it has been reported that three percent of the world-wide energy is consumed by the ICT (Information & Communications Technology) infrastructure that causes about two percent of the world-wide CO2 emissions [1]. Therefore, now it is time for the ICT society to include the objective of energy saving in the evolution path of the next generation wireless networks, i.e. to investigate *green communications*.

With its inherent intelligence, Secondary Users (SUs) in a Cognitive Radio Network (CRN) are able to interact and learn from their radio environment, adaptively change their working parameters (power, bandwidth, frequency, etc.) to dynamically utilize the unused spectrum of Primary Users (PUs). Due to its powerful cognitive capabilities, Cognitive Radio (CR) opens up a new direction and possibility for green communications [2]. New functionalities introduced in

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CRN bring unparalleled agility, but at the same time introduce additional power consumption. One of the major overheads is the spectrum sensing procedure, which is required before SUs could access the PU channels.

In this paper, we study the energy consumption in CRNs due to the spectrum sensing. Specifically, we focus on the cooperative sensing technology, which is considered to be a promising spectrum sensing technology for practical implementation [3]. The scheduling problem is the most critical issue in cooperative sensing. Basically, for a CRN applying cooperative sensing, two questions should be answered:

(1) How to select the set of SUs for spectrum sensing?
(2) Given this set of SUs, how to assign them to sense different PU channels?

For the first question, selecting more SUs for sensing implies higher expected throughput; but on the other hand, the energy consumed in the sensing will also increase. Therefore, this question reveals the tradeoff between throughput and energy. For the second question, assigning more SUs to sense one channel can improve sensing accuracy, but in return will lose some spectrum opportunity since less channels are exploited. This question gives rise to the tradeoff between opportunity and accuracy, which is referred as the Cooperative Sensing Scheduling (CSS) problem in our previous works [4]. The two questions lead to two dimensional tradeoffs, which should be jointly optimized. In this paper, we thoroughly analyze this Spectrum Opportunity-Energy Tradeoff (SOET) problem. We exploit the solution structure and show some interesting properties. Based on the analytical results, we develop an efficient algorithm to obtain the optimal solutions. Our algorithm and results apply for arbitrary number of SUs and PU channels.

The rest of the paper is organized as follows. The system model is presented in Section 2. We formulate the SOET problem in Section 3. In Section 4, the inherent structure of the problem is studied and the algorithm for finding the optimal solutions is provided. Numerical results are given in Section 5 and we conclude this paper in Section 6.

2 System Model

Suppose there are N PU channels denoted by $\mathcal{N} \triangleq \{1, ..., N\}$ which can be opportunistically accessed by SUs. Let $s_n = 0$ and $s_n = 1$ denote that the occupancy state of channel $n \in \mathcal{N}$ being idle and busy, respectively. The CRN of our interest consists of M SUs and a Base Station (BS), which is responsible for scheduling and assigning SUs to sense PU channels, collecting individual sensing results and making the final decision on the occupancy state of PU channels.

Assume that the CRN works in a slotted frame structure as mentioned in [5] and the length of each frame is fixed to T. Each frame consists of three durations: a fixed sensing duration τ, a fixed scheduling and results fusing duration η, and a data transmission duration $T - \tau - \eta$. In the sensing duration, each SU selected for sensing will sense PU channels using energy detection [5] and each SU can only sense one channel due to physical limitations. Suppose the PU signals are complex-valued PSK signals while the noise is the Circular Symmetric Complex Gaussian (CSCG) [5] [6]. Let the sensing performance of each SU, i.e. detection probability and false alarm probability, be denoted by p_d and p_f respectively, then the relationship between them is given by [5]

$$p_f = Q(\sqrt{2\gamma + 1}Q^{-1}(p_d) + \sqrt{\tau f_s}\gamma), \tag{1}$$

where γ denotes the signal-to-noise ratio (SNR) of the PU signals received at SU and f_s represents the sampling rate[1], $Q(\cdot)$ denotes tail probability of the standard Gaussian distribution and $Q^{-1}(\cdot)$ is the inverse of $Q(\cdot)$.

Under the context of cooperative sensing, each SU will report its one bit sensing result (idle or busy) to the BS after sensing its assigned PU channel. Then the BS will perform results fusion to generate final decision on the occupancy state of PU channels using "OR" rule [7]. Suppose channel $n \in \mathcal{N}$ is cooperatively sensed by m SUs. Similar to [6] [8], we assume the received SNR at each SU is identical and denoted as γ. The discussion on heterogeneous SNR will be left as our future work. In this case, the sensing performance of channel n at the BS can be described as

$$P_d^n(m) = 1 - [1 - p_d^n(m)]^m, \; P_f^n(m) = 1 - \left[1 - p_f^n(m)\right]^m, \tag{2}$$

where $p_d^n(m)$ and $p_f^n(m)$ denote the detection probability and false alarm probability of individual SU that senses channel n, respectively.

3 Problem Formulation

As aforementioned, two tradeoffs need to be tackled in this paper. The first one is between expected throughput and sensing energy consumption, i.e. if we let more SUs participate in sensing, the CRN can get higher expected throughput whereas the energy consumption also increases. This tradeoff could be tackled by finding a proper set of SUs to participate in the sensing process. Because of the homogeneous assumption of SUs, this problem becomes selecting an appropriate number of SUs to sense PU channels. The other tradeoff is between the exploration of spectrum opportunity and sensing accuracy, namely, if more SUs are assigned to sense one channel, the sensing accuracy can be improved while the spectrum opportunity may not be fully explored. To tackle this tradeoff is to find a proper assignment of SUs to sense PU channels such that a good balance between spectrum opportunity exploration and sensing accuracy is achieved.

Denote κ as the total number of SUs participated in sensing and $\mathbf{a}(\kappa) \triangleq \{a_n \mid \sum_{n=1}^{N} a_n = \kappa, n \in \mathcal{N}\}$ as the assignment of SUs, where a_n is the number of SUs assigned to sense channel $n \in \mathcal{N}$. Then the objective of the BS is to select an optimal number of SUs to participate in sensing and to find an optimal assignment of selected SUs so that a good balance between expected throughput and energy consumption is achieved. The expected throughput of the CRN is expressed as

[1] Note that τ and f_s are decided by the BS, and are the same for all SUs.

$$\widetilde{R}(\mathbf{a}(\kappa)) = \frac{T-\tau-\eta}{T} \sum_{n:a_n>0} \left\{ C_0[1-P_f^n(a_n)]\Pr(s_n=0) + C_1[1-P_d^n(a_n)]\Pr(s_n=1) \right\}, \tag{3}$$

where C_0 and C_1 denote the throughput of CRN when it operates in the absence and presence of PUs, respectively. Let $\Pr(s_n = 0)$ and $\Pr(s_n = 1)$ denote the stationary probability that channel n is idle and busy, respectively. Without loss of generality, we assume $\Pr(s_n = 0)$ and $\Pr(s_n = 1)$ are the same for all channels. The case that channels with different stationary probabilities will be left as our future work. According to [5], $C_0 >> C_1$ and the throughput of the CRN when PUs are absent dominates. As a result, the expected throughput can be rewritten as

$$R(\mathbf{a}(\kappa)) = \frac{T-\tau-\eta}{T} \sum_{n:a_n>0} \left\{ C_0[1-P_f^n(a_n)]\Pr(s_n=0) \right\}. \tag{4}$$

The energy consumption of the CRN during the sensing process is given by $E(\kappa) = \tau\phi\kappa$, where ϕ is the power spent for sensing. After taking both expected throughput and energy consumption into consideration, the utility function of the OE tradeoff problem can be defined as

$$U(\mathbf{a}(\kappa), \kappa) = w_t R(\mathbf{a}(\kappa)) - w_e E(\kappa), \tag{5}$$

where w_e and w_t are the weighting factors for throughput and energy consumption, respectively. These two weighting factors reflect how the CRN evaluates the importance of the two conflicting objectives mentioned above.

In order to protect the priority of PUs, SUs are required to achieve a specific probability of detection, $\bar{P}_d^n$, for each PU channel n they sense. Without loss of generality, we assume $\bar{P}_d^n = \bar{P}_d$, $\forall n \in \mathcal{N}$. Therefore, the SOET problem can be formulated as

$$(\mathbf{P1}): \max_{\mathbf{a}(\kappa),\kappa} U(\mathbf{a}(\kappa), \kappa) \tag{6}$$

$$s.t. \;\; \kappa \leq M \tag{7}$$

$$\sum\nolimits_{n=1}^{N} a_n = \kappa, \; a_n \in \{0, 1, ..., \kappa\} \tag{8}$$

$$P_d^n(a_n) \geq \bar{P}_d, \; \forall n \in \mathcal{N}. \tag{9}$$

According to [5] [6], the optimal solution of problem (**P1**) is achieved with equality constraint in (9). Problem (**P1**) is a combinatorial optimization problem which is generally difficult to deal with. In the following sections, we will show some nice properties of this problem and propose efficient methods to solve it.

4 Analytical Analysis

To find the optimal solution of problem (**P1**), we decompose it into the following two subproblems:

Subproblem 1: Find the optimal assignment of SUs to sense the PU channels for a given number of SUs participated in sensing.

Subproblem 2: Find an appropriate number of SUs to participate in sensing so that a desirable balance between sensing energy consumption and expected throughput can be achieved.

In the remainder of this section, we will discuss these two subproblems one by one.

4.1 Subproblem 1: How to Assign SUs to Sense the PU Channels

In this subsection, we will propose an optimal assigning mechanism for SUs to sense PU channels for given number of SUs participated in sensing (i.e., κ). According to our previous work [4], we have the following Lemma 1, Proposition 1 and Theorem 1. Here we simply present existing results, please refer to [4] for detailed proof. To facilitate our analysis, we first present the following definition.

Definition: Let the combinations (i.e., the assigning methods for SUs to sense PU channels) in which exactly i PU channels are sensed form a *group* G_i, $i = 1, ..., I$, where $I = \min\{\kappa, N\}$. Also, denote the number of combinations in group G_i as $|G_i|$. The l-th ($l = 1, ..., |G_i|$) combination in group G_i is denoted as $C_{i,l} = \{a_{i,l}^j\}$ ($j = 1, ..., i$), where $a_{i,l}^j$ represents the number of SUs assigned to sense channel j.

We will omit all the superscripts n which indicates different channels in the rest of this paper, since all channels are homogeneous in terms of stationary probabilities and the SNR of the PU signals received at SUs are identical. Define $\nabla f(x)$ as the derivative of function $f(x)$ with respect to x, and we have the following Lemma 1.

Lemma 1. *Let m be a continuous variable representing the number of SUs assigned to sense a channel with domain $[1, +\infty)$. Then $P_f(m)$ is decreasing and convex, where m is the number of SUs assigned, if the following condition holds*

$$\left[\ln(1 - p_f(m)) - \frac{m}{1 - p_f(m)}\nabla p_f(m)\right]^2 < \frac{2\nabla p_f(m) - m\nabla^2 p_f(m)}{1 - p_f(m)} - \left[\frac{\sqrt{m}\nabla p_f(m)}{1 - p_f(m)}\right]^2. \tag{10}$$

In fact, condition (10) holds for most of practical systems. Hence, without loss of generality, we assume this condition (10) always holds in this paper. Under this assumption, we have the following Proposition 1, which shows how to optimally assign SUs to sense PU channels.

Proposition 1. *For $i = 1, ..., I$, let $C_{i,\max}$ denote the combination that produces the largest value of the objective function (6) in group G_i, where*

$$a_{i,\max}^j = \lceil \frac{\kappa}{i} \rceil \text{ or } a_{i,\max}^j = \lfloor \frac{\kappa}{i} \rfloor, \; j = 1, ..., i \tag{11}$$

and $\sum_j a_{i,\max}^j = \kappa$, then $C_{i,\max}$ ($i = 1, ..., I$) has the following property:

$$\sum_j P_f(a^j_{i,\max}) \leq \sum_j P_f(a^j_{i,l}),\ l = 1, ..., |G_i|. \tag{12}$$

According to Proposition 1, the optimal number of SUs assigned to each channel is either $\lceil \frac{\kappa}{i} \rceil$ or $\lfloor \frac{\kappa}{i} \rfloor$, where i is the number of sensed PU channels. That is to say, SUs are spread out to all the channels that the CRN determined to sense as evenly as possible. Here another problem arises: how many channels the CRN should sense in order to produce the largest value of objective function (6). The following Theorem 1 will answer it.

Theorem 1. *The optimal solution of Subproblem1 is $C_{I,\max}$, i.e. to assign each SU to sense one different channel respectively, if the condition*

$$2P_f(1) - P_f(2) - 1 < 0 \tag{13}$$

holds, which is a necessary and sufficient condition.

Theorem 1 shows that if condition (13) holds, the CRN will reach its capacity in terms of the number of sensed PU channels (i.e., sense I PU channels). According to [4] and extensive simulations, condition (13) always holds in practical systems, for example, under the parameters used in [5] as well as in section 5 of this paper. In this paper, we only focus on practical systems and assume that condition (13) holds throughout this paper.

4.2 Subproblem 2: How to Select the Number of SUs for Sensing

Our objective in this subsection is to find an appropriate number of SUs to participate in sensing such that a desirable balance between sensing energy consumption and expected throughput can be obtained. To find the optimal solution, we need to first figure out the structure of the utility function (6), i.e. how the utility function varies with respect to different κ. The following Proposition 2 can answer this question.

Proposition 2. *Denote $U(\mathbf{a}^*(\kappa), \kappa)$ as the utility function (6) under the optimal SU assigning mechanism for given κ SUs (i.e., the given κ SUs are assigned according to the optimal assigning method provided in Proposition 1). Also, let N' denote the number of PU channels selected for sensing. Define $\Delta U(\mathbf{a}^*(\kappa), \kappa) \triangleq U(\mathbf{a}^*(\kappa+1), \kappa+1) - U(\mathbf{a}^*(\kappa), \kappa)$ as the first difference of function $U(\mathbf{a}^*(\kappa), \kappa)$ with respect to κ. Then $\Delta U(\mathbf{a}^*(\kappa), \kappa)$ is piecewise constant.*

Proof. The first difference of $U(\mathbf{a}^*(\kappa), \kappa)$ with respect to κ can be given by

$$\Delta U(\mathbf{a}^*(\kappa), \kappa) = \alpha \Delta P(\mathbf{a}^*(\kappa), \kappa) - \beta, \tag{14}$$

where $\alpha = w_t \frac{T-\tau-\eta}{T} C_0 Pr(s_n = 0)$, $\beta = w_e \tau \phi$, $P(\mathbf{a}^*(\kappa), \kappa) = \sum_{n:a_n>0}[1 - P^n_f(a_n)]$, and $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ is the first difference of $P(\mathbf{a}^*(\kappa), \kappa)$, which is similarly defined as $\Delta U(\mathbf{a}^*(\kappa), \kappa)$. Since the second term in (14) is constant, we only need to delve into the first term.

Denote J as the quotient and K as the remainder of the division $\frac{\kappa}{N'}$, i.e. $\kappa = JN' + K$. Since κ SUs, in total, engage in sensing, K channels are sensed by $\lceil \frac{\kappa}{N'} \rceil$ SUs and $(N' - K)$ channels are sensed by $\lfloor \frac{\kappa}{N'} \rfloor$ SUs. Suppose one more SU participates in sensing, then it will be assigned to one of these $(N' - K)$ channels which are sensed by $\lfloor \frac{\kappa}{N'} \rfloor$ SUs. According to Proposition 1, now the optimal assignment $a^*(\kappa + 1)$ is that $(K + 1)$ channels are sensed by $\lceil \frac{\kappa}{N'} \rceil$ SUs and $(N' - K - 1)$ channels are sensed by $\lfloor \frac{\kappa}{N'} \rfloor$ SUs. Therefore, the improvement of $P(\mathbf{a}^*(\kappa), \kappa)$ after adding one additional SU is given by

$$\Delta P(\mathbf{a}^*(\kappa), \kappa) \triangleq P(\mathbf{a}^*(\kappa+1), \kappa+1) - P(\mathbf{a}^*(\kappa), \kappa) = P_f(\lfloor \frac{\kappa}{N'} \rfloor) - P_f(\lceil \frac{\kappa}{N'} \rceil). \quad (15)$$

From (15), we can conclude that $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ is identical within each interval, where $\kappa \in [(j-1)N', jN' - 1]$, $j = 1, ..., J$. This completes the proof.

It is worth mentioning that the analysis above reveals that the value of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ only changes when κ increases from jN' to $(jN' + 1)$, where $j = 1, ..., J$. We are interested in further exploring how $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ changes with respect to κ, hoping that more insights can be found. Here we use N' to denote the number of PU channels selected to sense. According to Theorem 1, we have $N' = \min\{M, N\}$. Here we have two scenarios: (1) when $M \leq N$, κ PU channels will be sensed, and each channel is sensed only by one SU; (2) when $M > N$, all the PU channels will be sensed and some channels will be cooperatively sensed by more than one SU. For the rest of the paper, we only study the second scenario and assume $M > N$ (i.e., $N' = N$) since the first scenario is a special case of the second one. Define $\delta_j \triangleq \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN-1} - \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN}$ as the change for the value of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ when κ increases from $(jN - 1)$ to jN, where $j = 1, ..., J$. The following Proposition 3 summarizes the properties of δ_j.

Proposition 3. *δ_j is positive and monotonically decreasing with respect to j, where $j = 1, ..., J$.*

Proof. From (15) and Lemma 1, we have

$$\begin{aligned} \delta_j &= \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN-1} - \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN} \\ &= \big[P_f(J-1) - P_f(J)\big] - \big[P_f(J) - P_f(J+1)\big] > 0, \end{aligned} \quad (16)$$

and

$$\begin{aligned} &\delta_j - \delta_{j+1} \\ &= \big\{\Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN-1} - \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN}\big\} \\ &-\big\{\Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=(j+1)N-1} - \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=(j+1)N}\big\} \\ &= \big\{\big[P_f(J-1) - P_f(J)\big] - \big[P_f(J) - P_f(J+1)\big]\big\} \\ &-\big\{\big[P_f(J) - P_f(J+1)\big] - \big[P_f(J+1) - P_f(J+2)\big]\big\} > 0. \end{aligned}$$

Hence δ_j is positive and monotonically decreases with respect to j. The proof is completed.

Physical explanation of Proposition 3 is as follows. When $\kappa \leq N$, the improvement of $P(\mathbf{a}^*(\kappa), \kappa)$ by adding more SUs results from sensing more channels, while when $\kappa > N$, the improvement is due to improved sensing accuracy caused by cooperative spectrum sensing. Sensing more channels will result in larger improvement on expected throughput than merely improving the sensing accuracy of existing channels. Also, the marginal improvement of expected throughput caused by improved sensing accuracy decreases as κ increases. Based on Proposition 2 and Proposition 3, the optimal solution of problem (**P1**) is given by the following Theorem 2.

Theorem 2. *Denote κ^* as the optimal solution of problem (**P1**). The optimal solution κ^* has the following properties.*
(i) *Multiple optimal solutions, $\kappa^* = jN, jN+1, ..., (j+1)N-1$, exist when the following condition holds*

$$\Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN} = \frac{\beta}{\alpha}. \tag{17}$$

(ii) *Single optimal solution, $\kappa^* = jN$, exists when both of the following two conditions hold*

$$\Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN-1} > \frac{\beta}{\alpha},\ \Delta P(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN} < \frac{\beta}{\alpha}. \tag{18}$$

Proof. Since $U(\mathbf{a}^*(\kappa), \kappa) = \alpha \Delta P(\mathbf{a}^*(\kappa), \kappa) - \beta$ is a linear transformation of $P(\mathbf{a}^*(\kappa), \kappa)$, it shares the same property of $P(\mathbf{a}^*(\kappa), \kappa)$ as mentioned in Proposition 2 and Proposition 3. Therefore, the optimal value of problem (**P1**) occurs at the point when $\Delta U(\mathbf{a}^*(\kappa), \kappa) = 0$ or at the jumping point when $U(\mathbf{a}^*(\kappa), \kappa)$ changes from positive to negative. When condition (17) holds, $U(\mathbf{a}^*(\kappa), \kappa) = 0$ at points $\kappa = jN, ..., (j+1)N-1$. In this case, the improvement of expected throughput by assigning more SUs to sense PU channels just offsets the punishment for extra energy consumption caused by inserting additional SUs. In other words, the improvement in objective function (6) remains zeros for $\kappa = jN, jN+1, ..., (j+1)N-1$. When condition (18) holds, there is only one optimal solution for problem (**P1**). According to (18) and (14), we have

$$U(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN} - U(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN-1} > 0, \tag{19}$$

$$U(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN+1} - U(\mathbf{a}^*(\kappa), \kappa)_{\kappa=jN} < 0. \tag{20}$$

Inequality (19) means that by adding one additional SU to the CRN where $\kappa = jN-1$, the improvement of objective function (6) is still positive. Inequality (20) indicates that the improvement of objective function (6) becomes negative when one more SU is added to the CRN where $\kappa = jN$. Therefore, the optimal solution for problem (**P1**) is $\kappa^* = jN$ in the CRN where condition (18) holds.

4.3 Algorithm to Find the Optimal Solution of Problem (P1)

Based on the theoretical analysis in subsection 4.1 and 4.2, we propose the following algorithm **(A1)** to find the optimal solution of problem (**P1**). It is worth emphasizing that the efficiency of algorithm **(A1)** results from using the solution structure given by Theorem 2. In step 3, m is the number of SUs assigned for each channel, and the loop is executed at most $\lceil \frac{M}{N} \rceil$ times. The optimal solution is found by searching the point when $\Delta P < \lambda$ (i.e.,$\Delta U(\mathbf{a}^*(\kappa), \kappa) < 0$).

Algorithm (A1)

1: Given the objective function U, the total number of SUs M and the total number of PU channels N.
2: **Initialization:** Set $m = 1$, $J = 0$, $J' = 0$, $\Delta P = 0$ and $\lambda = \frac{w_e \tau \phi T}{w_t (T-\tau-\eta) C_0 Pr(s_n=0)}$
3: **Repeat** $\Delta P = P_f(m) - P_f(m+1)$, $m = m+1$
Until $\Delta P < \lambda$ or $m = \lceil \frac{M}{N} \rceil$
4: $J = m$
5: **if** $\Delta P < \lambda$ **then**
6: **if** $P_f(J-1) - P_f(J) = \lambda$ **then**
7: $\kappa^* = (J-1)N, (J-1)N+1, ..., JN-1$ and
$J' = J-1$
8: **else** $\kappa^* = JN$ and $J' = J$
9: **else** $\kappa^* = M$ and $J' = J-1$
10: $\mathbf{a}^*(\kappa^*) = \{J', ..., J', (J'+1), ..., (J'+1)\}$, where the number of J' is $(N-K)$ and the number of $(J'+1)$ is K, K is the remainder of the division $\frac{\kappa^*}{N}$, then stop.

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5 Numerical Results

In this section, we provide several numerical examples to illustrate and validate our analysis. The system parameters are selected similar to [5] and given as follows: the frame length is $T = 100ms$, while $\eta = 0.1T$ and $\tau = 5ms$. There are $N = 15$ PU channels, the required detection probability of each is $\bar{P}_d = 0.9$, and $\Pr(s_n = 0) = 0.7$, $\forall n$. The SNR of the received PU signal is $\gamma = -25dB$, sampling rate $f_s = 2$MHz and $C_0 = 6.6582$ [5]. For simplicity, we normalize $\alpha = w_t \frac{T-\tau-\eta}{T} C_0 Pr(s_n = 0)$ to 1.

Figure 1 shows the values of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ with respect to the number of SUs engaged in sensing, κ. It can be seen that the values of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ are piecewise constant, as we proved in Proposition 2. The jumping point occurs when the number of SUs engaged in sensing changes from $\kappa = JN$ to $\kappa = JN + 1$, and the improvement of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$ at the jumping point, i.e. δ_j, monotonically decreases as κ increases. The horizontal lines in both sub-figures denote different values of $\beta = w_e \tau \phi$. In the upper sub-figure, single optimal solution exists, i.e. to select 15 SUs to sense all 15 PU channels, as described in Theorem 2. In the lower sub-figure, the β value is identical to the improvement of adding one more SU for sensing, within the range of $\kappa = 16$ to $\kappa = 30$. In this case, as long as the number of SUs are selected within this range, it makes no difference to the objective value of problem (**P1**).

In Figure 2, we plot the objective value of $U(\mathbf{a}(\kappa), \kappa)$ versus the number of SUs engaged in sensing, κ. Both sub-figures show that the objective function is unimodal and possesses single optimal solution if (18) holds. It can also be observed that if the total number of PU channels available increases, the optimal objective value increases as well. The reason is under practical system parameters, condition (13) always holds, and the CRN will exploit as many channels as possible to fully make use of the under-utilized spectrum.

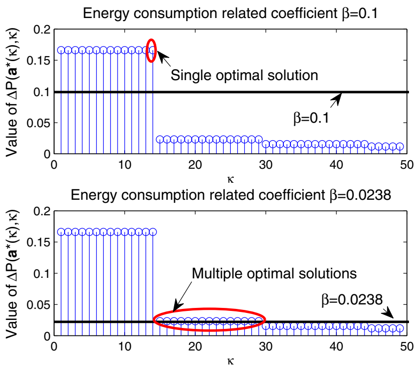

Fig. 1. Illustration of the value of $\Delta P(\mathbf{a}^*(\kappa), \kappa)$

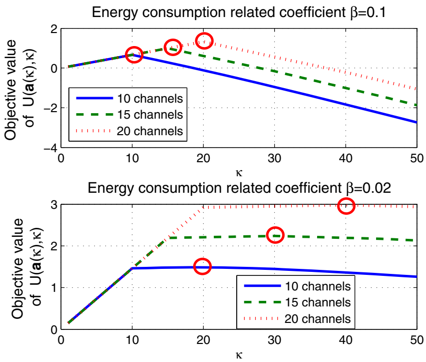

Fig. 2. Value of the objective function $U(\mathbf{a}(\kappa), \kappa)$ with respect to different number of PU channels

6 Conclusions

In this paper, the SU selection and assignment issues of the CRN are studied under the context of cooperative spectrum sensing. These two issues can be formulated as a two dimensional SOET problem. In order to find the optimal solution, we decompose the SOET problem into two subproblems. By solving these two subproblems, we find the optimal number of SUs participated in sensing and the optimal assignment of these SUs to sense PU channels. Finally, the optimal solution structure of the SOET problem is presented and some useful properties are shown. Based on these properties, we propose an efficient algorithm to obtain the optimal value of the SOET problem under practical system parameters. Numerical results are also presented to verify the theoretical analysis. In the future, we will deal with the case where SUs have heterogenous sensing capability and PU channels have heterogenous requirements in terms of detection probability.

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