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Optimal Throughput of Secondary Users over Two Primary Channels in Cooperative Cognitive Radio Networks

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Abstract

In this paper, we investigated the throughput of a cognitive radio network where two primary frequency channels (PCs) are sensed and opportunistically accessed by N secondary users. The sharing sensing member (SSM) protocol is introduced to sense both PCs simultaneously. According to the SSM protocol, N SUs (Secondary User) are divided into two groups, which allows for the simultaneous sensing of two PCs. With a frame structure, after determining whether the PCs are idle or active during a sensing slot, the SUs may use the remaining time to transmit their own data. The throughput of the network is formulated as a convex optimization problem. We then evaluated an iterative algorithm to allocate the optimal sensing time, fusion rule and the number of members in each group. The computer simulation and numerical results show that the proposed optimal allocation improves the throughput of the SU under a misdetection constraint to protect the PCs. If not, its initial date of receipt shall be nullified.

Key words: Cognitive Radio, Cooperative Spectrum Sensing, Rayleigh Fading Channel.

Ⅰ. Introduction

Cognitive radio has recently gained much consideration for resolving the conflict between the steady spectrum demand of unlicensed users (secondary users, SUs) and the inefficient spectrum utilization of licensed users (primary users, PUs) [1]. In order to access a primary channel without damaging the transmission of the licensed network, the SUs must sense and identify whether or not the licensed channel is inactive. The secondary network can operate on the PU's spectrum only if the primary channels are idle. Hence, spectrum sensing problems in cognitive radio systems have received much attention, with the aim of developing a system to detect the spectrum holes.

Various sensing techniques have been studied [2], [3], and these techniques can be divided into three categories: energy detection, matched filter detection, and cyclostationary detection. Among these, energy detection has been widely applied since it does not require any a priori knowledge of the PU signals and it has a much lower complexity when compared to other methods. Furthermore, cooperative spectrum sensing has been proposed to exploit multiuser diversity in the sensing process as a way of addressing the fading and shadowing problem [4], [5]. Improved sensing performance in the sensing scheme will require sensing time. However, a longer time required for sensing will reduce the data transmission duration.

The trade-off between sensing and throughput was considered by Ying-Chang and Peh [6], [7], who proposed a frame organization including a spectrum sensing slot and communication slot for SUs and studied the approximate throughput. Previous studies agree that the sensing time over which SUs detect the PUs' activity should be optimized in order to maximize the throughput of the SUs as well as the overall system performance [3], [4]. Nevertheless, most optimal sensing/ throughput tradeoff studies to date have concentrated on the case in which only one primary channel is considered. A spectrum sensing system focused on independent channels was addressed by Kim [8]. However, a scheme with one secondary user is not a good choice for a cognitive radio network consisting of multi-users.

In this paper, a cooperative spectrum sensing scheme is considered for sensing and accessing two primary channels. Under the assumption that the secondary user cannot sense two channels concurrently, we propose a sharing sensing member (SSM) protocol which allows simultaneous fusion of the two channels. The frame structure of the secondary radio network, including a sensing time slot and a data transmission slot, was studied. The approximate throughput of the cognitive radio network was then generated as the target function for optimizing the parameters of the network. An algo-

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rithm is described for determining the optimal sensing time, fusion rule, and the member number of each group in order to maximize the throughput. Based on this algorithm, an optimal sensing method is proposed, which outperforms the other methods in cases of different channels. Finally, we evaluated the optimal results through simulations and considered the benefits of optimal parameters for the network throughput.

Ⅱ. System Models

2-1 System Model

We consider a cognitive radio network where N secondary users sense and access two primary channels. The cooperative spectrum sensing strategy recognizes each PC, such that every secondary user makes their own binary decision on the status of the PC and then reports these bits to the secondary base station. The final decision is then made according to the k-out-of-N fusion rule. We denote the two primary channels as PC1 and PC2. The secondary network senses PC1 and PC2 and accesses the channel to send the data if the primary channel is idle within a fixed frame time, T. We assume that the SU cannot sense two PCs simultaneously. Hence, in order to detect the idle channels and employ them, we divided all SUs into two groups, with each group sensing a channel. Based on this consideration, we focus on the protocol by which N secondary users can share the sensing members (SSM) in order to sense and use the PCs.

2-1-1 SSM Protocol

This protocol is similar to that in which two secondary networks sense and share two different channels with the primary networks [7]. N secondary users are divided into two groups for the simultaneous sensing of two channels. Each channel, if detected to be idle, can be used to send the data by the cognitive radio network (Fig. 1).

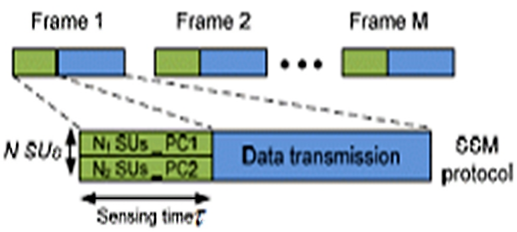

Fig. 1. Frame structure of the secondary radio network accessing the primary channels with the sharing sensing members protocol (SSM).

2-2 Energy Detection

In this paper, we assume that the energy detector is employed by each user to sense the primary channel. If the PC i (i = 1, 2) is idle, the signal received at the j-th SU is just noise denoted by $y_j^i(n) = u_j(n)$, where $u_j(n)$ is assumed to be a circularly symmetric complex Gaussian with a zero mean and a variance of σ_u^2. If the primary channel occurs by the licensed network, the received signal is given by $y_j^i(n) = h_j^i s(n) + u_j^i(n)$, where $s(n)$ is the signal over the primary channel, i , while the average power is 1. h_j^i is the channel gain of the channel, i, at the j-th SU, which is presumed to be a circularly symmetric complex Gaussian with a zero mean and a variance of σ_i^2. Hence, we assume the same signal-to-noise ratio (SNR) of the i-th primary channel for all SUs, which can be expressed $\gamma_i = \sigma_i^2 / \sigma_u^2$. The test statistic for the primary channel, i, is defined as $Y_i = \sum_{n=1}^{W_i} | y_j^i(n) |^2$, where $W_i = \tau_i f_s$ is the number of samples during the sensing duration, τ_i and with a sampling frequency of f_s. The status of the primary channel, i, can be defined by comparing the test statistic, Y_i, with a certain threshold, ε (assuming the same energy threshold for both channels). Hence, the probabilities of detection and false alarm for each channel at each SU [6] are given by

$$P_{d,i}(\tau_i) = Q\left(a_i \sqrt{T_i}\right) \tag{1}$$

$$P_f(\tau_i) = Q\left(b_i \sqrt{T_i}\right) \tag{2}$$

where $Q(x) = \left(1/\sqrt{2\pi}\right)\int_x^{\infty} e^{-t^2/2} dt$ denotes the Q function, $Q^{-1}(\cdot)$ is the inverse function of $Q(\cdot)$, $a_i = \left[\varepsilon / \sigma_u^2 (1+\gamma_i) - 1\right]\sqrt{f_s}$ and $b_i = \left[\varepsilon / \sigma_u^2 - 1\right]\sqrt{f_s}$. Cooperative sensing is applied after making a binary decision at each cognitive user (CU). All the local decisions are forwarded to the fusion center (FC). At the FC, all the signals from the CUs are fused together according to logic "k-out-of-n" fusion rule [4]. The probabilities of detection and false alarm at the fusion center are then given by the following equations, respectively:

$$P_{d,i}(\tau_i, k, n) = \sum_{l=k}^{n} \binom{n}{l} p_{d,i}(\tau_i)^l \left[1 - p_{d,i}(\tau_i)\right]^{n-l} \tag{3}$$

$$P_f(\tau_i, k, n) = \sum_{l=k}^{n} \binom{n}{l} p_f(\tau_i)^l \left[1 - p_f(\tau_i)\right]^{n-l} \tag{4}$$

Ⅲ. Sensing-Throughput Tradeoff with the SSM Protocol

3-1 Formulation of the Optimization Problem

In Fig. 1, the frame structure of a cognitive radio network with the SSM protocol is divided into two parts: the sensing slot, τ , and the data transmission slot, (T$-\tau$). During the sensing time, instead of sharing the time to focus on two channels, as previously performed [8], the SSM scheme divides N SUs into two groups to sense two channels simultaneously. N_1 and N_2 are the numbers of SUs in the two groups that focus on PC1 and PC2, respectively. Hence, $N = N_1 + N_2$. The two groups apply two independent " k-out-of-n" fusion rules, denoted by two integers, k_1 and k_2, respectively. Each primary channel is associated with two possible scenarios for the secondary users to utilize the channel: right detection when the PC is free and wrong detection when it is busy. The probability of the two scenarios for each primary channel can be given by

$$\mathrm{Pr}_i^{id} = p_i\left(1 - P_{f,i}\left(\tau, k_i, N_i\right)\right) \tag{5}$$

$$\mathrm{Pr}_i^{ac} = \left(1 - p_i\right)\left(1 - P_{d,i}\left(\tau, k_i, N_i\right)\right) \tag{6}$$

where Pr_i^{id} and Pr_i^{ac} are the probabilities that the secondary network can use the channel i, if that channel is idle or active, respectively. p_i denotes the probability that the PCi is inactive, $P_{f,i}\left(\tau, k_i, N_i\right)$ and $P_{d,i}\left(\tau, k_i, N_i\right)$ are the false alarm and detection probabilities of group i that can be defined based on equations 3 and 4, respectively. The throughputs of the secondary users over the primary channel PCi under the first and second scenarios are denoted as C_i^{id} and C_i^{ac}, respectively. It is easy to see that $C_i^{id} > C_i^{ac}$ because of the interference between the two networks in the second scenario. Furthermore, to protect the primary network, we must design the sensing scheme such that $P_{d,i}\left(\tau, k_i, N_i\right) \approx 1$. Hence, the throughput of the first case is much greater than the second case. Thus, the total average throughput of the secondary network over two primary channels can be approximately given as

$$R_i^{id}\left(\tau, k_i, N_1\right) = \sum_{i=1}^{2} R_i^{id}\left(\tau, k_i, N_i\right) \tag{7}$$

where $R_i^{id}\left(\tau, k_i, N_i\right)$ is the throughtput of the first scenario for each PC that can be described as

$$R_i^{id}\left(\tau, k_i, N_i\right) = C_i^{id}\left(1 - \frac{t}{T}\right)\mathrm{Pr}_i^{id} \tag{8}$$

From equation (7), the problem formulation of the sensing-throughput tradeoff with cooperative sensing is given as

$$\begin{aligned} &\underset{\tau, k_1, k_2, N_1}{\text{maximize}} \quad R\left(\tau, k_1, k_2, N_1\right) \\ &s.t.\ P_{d,1}\left(\tau, k_1, N_1\right) \geq \overline{P}_{d,1}; P_{d,2}\left(\tau, k_2, N - N_1\right) \geq \overline{P}_{d,2} \quad (a) \\ &\qquad 1 \leq k_1 \leq N_1; 1 \leq k_2 \leq N - N_1 \quad (b) \\ &\qquad 0 \leq \tau \leq T \quad (c) \end{aligned} \tag{9}$$

where $\overline{\mathrm{P}}_{d,i}\left(i = 1, 2\right)$ is the minimum probability of detection that secondary network must achieve to protect the primary network. Here, from equation (3) for any given $P_{d,i}$, k_i and N_i, we can always define $\overline{\tau}_i$ such that $P_{d,i}\left(\overline{\tau}_i\right) = \overline{P_{d,i}}\left(k_i, N_i\right)$ and $\sum_{l=k_i}^{N_i} \overline{P_{d,i}}\left(k_i, N_i\right)^l \left[1 - \overline{P_{d,i}}\left(k_i, N_i\right)\right]^{N-l}$ $= \overline{P_{d,i}}$. Based on [8], the value of $\overline{\tau}_i$ can be given as

$$\overline{\tau}_i = \left(p_i / a_i\right)^2 \tag{10}$$

where $p_i = Q^{-1}\left(\overline{p}_{d,i}\left(k, N\right)\right)$.

Then, the constraint (9a) can become the constraint of τ as $\tau \geq \max\left(\overline{\tau}_1, \overline{\tau}_2\right)$. Hence, we can rewrite the optimization problem in (9) as

$$\underset{\tau, k_1, k_2, N_1}{\text{maximize}} \quad R\left(\tau, k_1, k_2, N_1\right) \tag{11}$$

$$\begin{aligned} s.t. \quad &\max\left(\overline{\tau}_1, \overline{\tau}_2\right) \leq \tau \leq T \quad (a) \\ &1 \leq k_1 \leq N_1;\ 1 \leq k_2 \leq N - N_1 \quad (b) \end{aligned} \tag{12}$$

In the next section, an iterative algorithm is proposed for finding the solutions of τ, k_1, k_2, and N_1 in order to maximize the secondary network throughput over two primary channels.

3-2 Finding the Sensing Time and Sensing Fusion

It is easy to see that equation (11) has a feasible solution only if the duration time of a frame satisfies

$$T \geq \max\left(\overline{\tau_1}, \overline{\tau_2}\right) \tag{13}$$

First, we consider the case in which N_1 is given. Now, we optimize the sensing time, τ, and the fusion rule in the two groups is respectively represented by k_1 and k_2. An iterative algorithm derived is performed in a loop such that:

(a) In the m-th step with a given $\tau(m)$, the value $k_i\left(m+1\right)\left(i = 1, 2\right)$ that maximizes the throughput $R\left(\tau, k_1, k_2, N_1\right)$ in equation (11) is determined.

(b) Next, the value of k_i is set as $k_i\left(m+1\right)$, and τ(m

+1) is generated, which again makes highest use of the throughput.

(c) Continue similarly for the next step (m+1)-th.

This iterative process is carried out until $|\tau(m)-\tau(m-1)|<\mu$ where μ is the tolerance of the accuracy of the optimal value τ and $k_i(m)=k_i(m-1)$.

Here, the proposed algorithm contains two sub-optimization problems. The first problem is that for a given value of τ, the value of k_i must be optimized to maximize equation (9). The second problem is that the highest throughput must be determined with a certain value of k_i and the optimal τ, the highest throughput must be determined.

3-3 Optimizing the Fusion Rule

Based on equations (5), (7), and (8), it is easy to see that when τ and N_1 are given, $R(\tau,k_1,k_2,N_1)$ is higher for lower values of $P_{f,i}(\tau,k_i,N_i)$. Moreover, $P_{f,i}(\tau,k_i,N_i)$ decreases when k_i increases. However, k_i is constrained by the condition, $\overline{\tau_i}\le\tau$ where $\overline{\tau_i}$ depends on k_i as in equation (10). Therefore, the optimal value of k_i can be found by increasing k_i from 1 to N_i and stopping if $\overline{\tau_i}\le\tau$. This process is carried out by the Algorithm 1 which is presented as follows:

Algorithm 1: For a given τ and N_i, find the maximum value of k_i that $\overline{\tau_i}\le\tau$.

Input: τ, N_i

Initialization: $k_i^{(0)}=1$.

While $k_i<N_i$ do

Find $\overline{\tau_i}$ utilizing equation (10)

If $\overline{\tau}_i\le\tau$ then

$k_i^{(m)}=k_i^{(m-1)}+1$

else break

end If

end while

Output: k_i.

3-4 Optimal Sensing Time τ^*

For known values of k_1 and k_2, the optimization problem in equation (11) can be reduced to

$$\max\ \overline{R}(\tau) \tag{14}$$

$$s.t\ \max\left(\overline{\tau_1},\overline{\tau_2}\right)\le\tau\le T, \tag{15}$$

where,

$$\overline{R}(\tau)=\left(1-\frac{\tau}{T}\right)\left[C_1^{id}p_1\left(1-P_{f,1}(\tau)\right)+C_2^{id}p_2\left(1-P_{f,2}(\tau)\right)\right] \tag{16}$$

where $P_{f,i}(\tau)=P_f(\tau,k_i,N_i)$.

In order to find the optimal value of τ, we must consider the "radient" of $\overline{R}(\tau)$ over τ which can be given as

$$\nabla\overline{R}(\tau)=-\sum_{i=1}^{2}\frac{C_i^{id}p_i}{T}\left[(T-\tau)\frac{\partial P_{f,i}(\tau)}{\partial\tau}+1-P_{f,i}(\tau)\right] \tag{17}$$

where $\partial P_{f,i}(\tau)/\partial\tau$ can be given from equation (4) as

$$\partial P_{f,i}(\tau)/\partial\tau=\left(\partial p_f(\tau)/\partial\tau\right)f_i(\tau) \tag{18}$$

where

$$f_i(\tau)=\sum_{l=k_i}^{N_i}\binom{N_i}{l}p_f(\tau)^{l-1}\left[1-p_f(\tau)\right]^{N-l-1}\left(l-N_ip_f(\tau)\right) \tag{19}$$

and $\partial p_f(\tau)/\partial\tau$ is given as

$$\partial p_f(\tau)/\partial\tau=-b/\sqrt{8\pi\tau}\exp\left(-b^2\tau/2\right). \tag{20}$$

By substituting equations (18)~(20) into equation (17) and $\nabla\overline{R}(\tau)=0$, we can obtain the optimal values of sensing time. However, obtaining the closed-form solutions is very complex. Therefore, a search for the optimal values will be considered at this point. The second derivative of $\overline{R}(\tau)$ can be described based on $\nabla\overline{R}(\tau)$ as

$$\Delta\overline{R}(\tau)=-\sum_{i=1}^{2}\frac{C_i^{id}p_i}{T}\left[(T-\tau)\frac{\partial^2P_{f,i}(\tau)}{\partial\tau^2}-\frac{\partial P_{f,i}(\tau)}{\partial\tau}\right] \tag{21}$$

where,

$$\partial^2P_{f,i}(\tau)/\partial\tau^2=\left(\partial^2p_f(\tau)/\partial\tau^2\right)f_i(\tau)+\left(\partial p_f(\tau)/\partial\tau\right)^2\left(\partial f_i(\tau)/\partial\tau\right). \tag{22}$$

By differentiating equation (19), it is simple to show that $\partial f_i(\tau)/\partial\tau>0$. Moreover, $\partial^2p_f(\tau)/\partial\tau^2$ is also greater than 0 due to the following equation:

$$\partial^2 p_f(\tau)/\partial\tau^2 = b/\sqrt{32\pi\tau^3}\left(b^2+1/\tau\right)\exp\left(-b^2\tau/2\right). \quad (23)$$

On the other hand, $\partial P_{f,i}(\tau)/\partial\tau < 0$ because, $\partial p_f(\tau)/\partial\tau < 0$ in equation: (20) and $f_i(\tau) > 0$ for the low value of $p_f(\tau)$ in equation (19). Therefore, we can show that $\Delta\overline{R}(\tau) < 0$ for $\max\left(\overline{\tau}_1,\overline{\tau}_2\right) \le \tau \le T$, and Newton''s method [9] can be applied to define the optimal value of τ . The algorithm to find the optimal value τ_j for a given value of k_i can be given as

Algorithm 2: For the given "*k*-out-of-*n*" fusion rule in each group, and N_i, find the optimal τ that maximizes $\overline{R}(\tau_j)$.

Input: k_1, k_2, N_1, μ (μ is the tolerance of accuracy of τ)
Initialization: $\tau^{(0)} = T$ (start at the point that minimizes the throughput $\overline{R}\left(\tau^{(0)}\right) = 0$).
Repeat $\tau^{(h)} = \tau^{(h-1)} - \nabla\overline{R}\left(\tau^{(h-1)}\right)\big/\Delta\overline{R}\left(\tau^{(h-1)}\right)$,
Until $\left|\tau^{(h)} - \tau^{(h-1)}\right| < \mu$
Output: $\tau = \tau^{(h)}$.

3-5 Optimization of Both the Voting Rule and Sensing Time

In this section, we use the iterative algorithm to find the optimal sensing time and the fusion rule for each group with a given value of N_1. Then, since N_1 is an integer, we can run N_1 from 1 to *N* and choose the best parameters (τ, k_1, k_2, N_1) for the SSM scheme. This process can be described by Algorithm 3.

Algorithm 3: Find the optimal $\left(\tau^*, k_1^*, k_2^*, N_1^*\right)$ that maximizes the throughput $R\left(\tau, k_1, k_2, N_1\right)$.

Input: N, $\max\left(\overline{\tau}_1,\overline{\tau}_2\right)$.
Initialization: $R_{\max} = 0$.
For $N_1 =$ 1 to N do
  $\tau^{(0)} = T$, $m = 0$.
Repeat
  1) Given $\tau^{(m)}$, find $k_1^{(m)}$ and $k_2^{(m)}$ using Algorithm 1.
  2) Given $k_1^{(m)}$ and $k_2^{(m)}$, find $\tau^{(m+1)}$ using Algorithm 2.
  3) $m = m + 1$.
Until $\tau^{(m)} \equiv \tau^{(m-1)}$, $k_1^{(m)} \equiv k_1^{(m-1)}$ and $k_2^{(m)} \equiv k_2^{(m-1)}$.
  Calculate $R\left(\tau^{(m)}, k_1^{(m)}, k_2^{(m)}, N_1\right)$
  If $R\left(\tau^{(m)}, k_1^{(m)}, k_2^{(m)}, N_1\right) > R_{\max}$ then
    $\tau^* = \tau^{(m-1)}$; $k_1^* = k_1^{(m-1)}$;
    $k_2^* = k_2^{(m-1)}$; $N_1^* = N_1$.
    $R_{\max} = R\left(\tau^{(m)}, k_1^{(m)}, k_2^{(m)}, N_1\right)$
  End if
End for
Output: $\left(\tau^*, k_1^*, k_2^*, N_1^*\right)$

Ⅳ. Computer Simulation Results

In this section, we present computer simulation results in order to evaluate the sensing-throughput tradeoff with the SSM protocol and to compare with the numerical results presented above. The optimal values of the sensing time, the number of users (*N*) in each group, the "*k*-out-of-*n*" fusion rule, and the throughput can be achieved based on our proposed iterative algorithms or scanning all possible parameter values and choosing the best one using a computer.

We consider the cognitive radio network with 20 SUs (*N* = 20) and a frame duration time of 10 ms (*T* = 10 ms). The sampling frequency of the received signal for both channels was set at 6 MHz. The targeted probabilities of detection for the protection of the primary channels were set at $\overline{P_{d,1}} = \overline{P_{d,2}} = 0.9999$. To maintain reasonable values of the spectrum sensing performances, the threshold, ε, should be set to satisfy $\sigma_u^2 < \varepsilon < \sigma_u^2 + \min\left\{\sigma_1^2, \sigma_2^2\right\}$. Hence, in the simulation, we presumed that $\varepsilon = \sigma_u^2 + \min\left\{\sigma_1^2, \sigma_2^2\right\}/2$. The equal SNRs for both primary channels received at the SUs were set to vary from −22 dB to −6 dB with $C_1^{id} = 2$ and $C_2^{id} = 1$. Figs. 2 and 3 show the optimal values of N_1, N_2, k_1, k_2 and τ at different values of the SNR when $p_1 = 0.6$ and $p_2 = 0.4$. Clearly, our proposed iterative algorithm produces the same optimal values for N_1, N_2, k_1, k_2 and τ in the computer' exhaustive search. Fig. 2 demonstrates that there are no identical solutions for N_1, N_2, k_1, k_2,

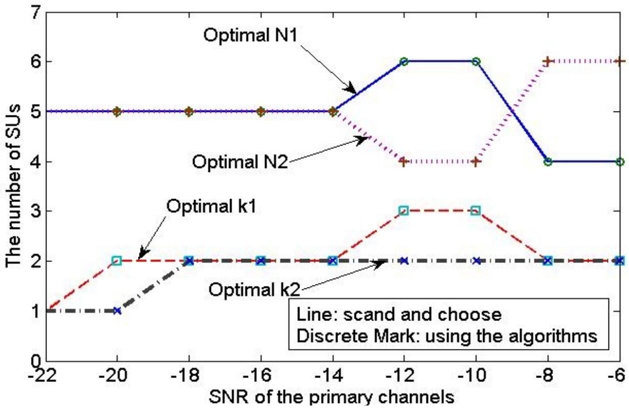

Fig. 2. Optimal number and the fusion rule for each group.

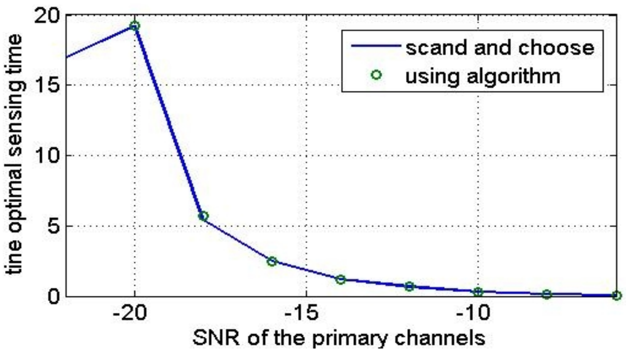

Fig. 3. Optimal sensing time that maximizes the throughput.

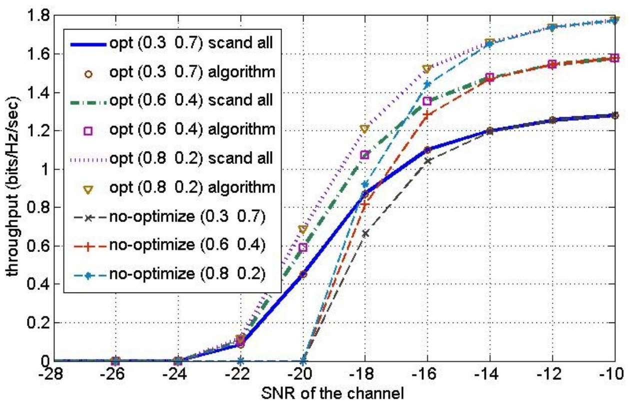

Fig. 4. The optimal throughput of the SSM scheme compared with a normal scheme when p_1=0.3, 0.6, 0.8 and p_2=0.7, 0.4, 0.2.

which are optimal for all cases, and in fact, different SNR values require different optimal values N_1, N_2, k_1, k_2 in order to maximize the throughput of the secondary network.

Fig. 4 illustrates the maximum normalized throughputs of the SSM scheme that were achieved by both the exhaustive search and the iterative algorithm for different values of p_1, p_2 including (0.3, 0.7), (0.6, 0.4), and (0.8, 0.2). The figure again shows good agreement between the two methods. The throughputs of the scheme when $N_1 = 6$, $N_2 = 4$, $k_1 = 3$, $k_2 = 2$ and $\tau = \max\left(\overline{\tau_1}, \overline{\tau_2}\right)$ are also shown for comparison with the optimal scheme and to show the benefits of optimization in maximizing the throughput.

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Ⅴ. Conclusion

In this paper, we present an optimal throughput of secondary networks over two primary channels using the sharing sensing member protocol. We provided an algorithm to allocate the optimal sensing time and fusion rule, and evaluated the number of members in each group. Under the constraint of mis-detection probability, the proposed allocation enhances the throughput of the SU compared with the equal allocation protocol.

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