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Cooperative spectrum sensing based on adaptive weighting for a cognitive radio system

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Abstract: We propose a combining scheme for hard decisions of secondary users to improve the performance of cooperative spectrum sensing in a cognitive radio system. In contrast to the conventional equal-weight combining, the proposed scheme assigns unequal weights to different users to form the global decision statistics. Specifically, the combining weights are updated adaptively such that a higher weight is given to the decision of a more reliable user. In order to update the weights, the fusion center estimates the reliability of each user based on the past recode of the user's local decisions. Numerical results show that the proposed scheme outperforms the equal-weight scheme and optimal scheme with counting method, especially when the channels from the primary transmitter to the secondary users are highly disparate.

Keywords: cooperative spectrum sensing, cognitive radio, decision combining

Classification: Science and engineering for electronics

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1 Introduction

With the explosive growth of wireless services, radio spectrum is considered as scarce and valuable resource. However, recent measurements have revealed that most of the licensed frequencies are under-utilized [1]. Cognitive radio is accepted as a solution for resolving the spectrum scarcity problem [2]. In cognitive radio systems, it is very important to protect the primary users from the potential interference that the secondary users may cause. Therefore, spectrum sensing is essential in cognitive radio systems [2].

The hidden-terminal problem limits the performance of local sensing of each user [2]. The reliability of spectrum sensing in such case can be improved by introducing cooperative spectrum sensing [3, 4]. For cooperation, each secondary user locally senses the spectrum, and reports the result to a fusion center. Then, the fusion center makes a global decision by combining the local decisions. The reported sensing result of each user can be either a hard or soft decision. It must be noted that the reliability of local decisions will be different due to different channel conditions. The reliability of soft decisions is naturally reflected into the global decision, as in the maximal ratio combining [3]. In the case of hard decisions, however, the reliability information becomes lost in the decision process of each user. The optimal combining of hard decisions requires the detection and false alarm probabilities of each user to be known to the fusion center [5], which makes it impractical.

We propose a combining scheme of local decisions, when each secondary user makes one-bit hard decisions. In the proposed combining scheme, the fusion center exploits the past recode of each secondary user's local decisions to estimate the reliability of the user without a prior knowledge. The reliability estimate is used to update the combining weight of the corresponding user.

2 Cooperative spectrum sensing

We consider a cooperative sensing scenario where K secondary users are cooperating under the control of a fusion center. The feedback channel from each secondary user to the fusion center is assumed to be error-free. Each secondary user is assumed to perform local sensing using an energy detector.

Let $\mathcal{H}_1$ and $\mathcal{H}_0$ denote a hypothesis that the primary signal is present and a hypothesis that it is absent, respectively. Then, the output of the energy detector for the k-th user at the n-th sensing interval can be expressed under each hypothesis as

$$E_k[n] = \begin{cases} \sum_{\ell=1}^{L} |v_k[n,\ell]|^2, & \mathcal{H}_0 \\ \sum_{\ell=1}^{L} |s_k[n,\ell] + v_k[n,\ell]|^2, & \mathcal{H}_1 \end{cases} \tag{1}$$

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where $s_k[n,\ell]$ and $v_k[n,\ell]$ denote the ℓ-th sample of the received signal and noise, respectively, in the n-th sensing interval, and L is the number of accumulated samples in a sensing interval. Each secondary user makes a hard decision by comparing $E_k[n]$ with a threshold γ_k. The corresponding binary decision $d_k[n] \in \{0,1\}$ of the k-th user can be expressed as

$$d_k[n] = u(E_k[n] - \gamma_k) \tag{2}$$

where $u(\cdot)$ denotes the unit step function. $d_k[n] = i$ means that the k-th user decides that the hypothesis $\mathcal{H}_i$ is true $(i = 0, 1)$. The local decision $d_k[n]$ is reported to the fusion center through a feedback channel.

The fusion center combines the local decisions to form the global decision statistics, which is compared with a decision threshold γ to extract the final decision. Let $\mathcal{F}(\cdot)$ denote the combining function, then the final decision $d[n]$ is given as

$$d[n] = u(\mathcal{F}(d_1[n], d_2[n], \cdots, d_K[n]) - \gamma). \tag{3}$$

3 Decision combining

3.1 Equal-weight combining

The simplest combining scheme of hard decisions will be equal-weight combining. The corresponding combining function can be written as

$$\mathcal{F}(d_1[n], d_2[n], \cdots, d_k[n]) = \frac{1}{K}\sum_{k=1}^{K} d_k[n]. \tag{4}$$

In this case, different choices of the threshold γ yield different decision rules; $\gamma = 1, 1/K$, and $1/2$ correspond to the AND rule, OR rule, and majority logic rule, respectively [4].

3.2 Optimal combining

The optimal combining rule can be derived from the Bayesian detection theory [5], and the corresponding combining function is given as

$$\mathcal{F}(d_1[n], d_2[n], \cdots, d_k[n]) = \ln \frac{P(d_1[n], d_2[n], \cdots, d_k[n]|\mathcal{H}_1)}{P(d_1[n], d_2[n], \cdots, d_K[n]|\mathcal{H}_0)}. \tag{5}$$

Under the assumption that local decisions are independent of one another, (5) can be expressed as [5]

$$\mathcal{F}(d_1[n], d_2[n], \cdots, d_k[n]) = \sum_{k \in \mathcal{S}_1[n]} \ln \frac{P_{D_k}}{P_{F_k}} + \sum_{k \in \mathcal{S}_0[n]} \ln \frac{1 - P_{D_k}}{1 - P_{F_k}}. \tag{6}$$

where $\mathcal{S}_i[n]$ is defined to be the set of users associated with $d_k[n] = i$ $(i = 0, 1)$, and $P_{D_k} \equiv P(d_k[n] = 1|\mathcal{H}_1)$ and $P_{F_k} \equiv P(d_k[n] = 1|\mathcal{H}_0)$, respectively, denote the detection probability and false alarm probability of the k-th user.

The optimal combining in (6) requires knowledge on the detection and false alarm probabilities of each user as well as a prior probabilities of the two hypotheses for the primary signal. Since these are generally unknown to the fusion center, the optimal combining is hard to implement. In [6], a

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counting method was proposed to estimate the probabilities. However, the counting method may be inaccurate, when the number of data is insufficient and/or the channel is time-varying.

3.3 Proposed adaptive combining

From (6), we observe that the local decision of a user associated with higher detection probability and lower false alarm probability contributes more to the global decision statistics, which implies that a higher weight should be given to a more reliable user. The proposed scheme assigns unequal weights to the secondary users by taking reliability of the users into account. Correspondingly, the proposed combining function can be written as

$$\mathcal{F}(d_1[n], d_2[n], \cdots, d_k[n]) = \sum_{k=1}^{K} w_k[n] d_k[n] \tag{7}$$

where $w_k[n]$ represents the weight of the k-th user in the n-th sensing interval.

In order to get the weight $w_k[n]$ in (7) that reflects the reliability, we notice that the reliability of a user is mainly determined by the channel condition between the primary and secondary users. Therefore, the more reliable a user is, the more correct local decisions the user will make, when a primary signal exists in the spectrum. Specifically, the fusion center updates the weights of the users as

$$\begin{aligned} w_k[n] &= \begin{cases} w_k[n-1] \cdot 2^{d_k[n-1]-1}, & \text{if} \quad \mathcal{H}[n-1] = \mathcal{H}_1 \\ w_k[n-1], & \text{if} \quad \mathcal{H}[n-1] = \mathcal{H}_0 \end{cases} \\ w_k[n] &= \frac{w_k[n]}{\sum_{k=1}^{K} w_k[n]}, \qquad k = 1, 2, \cdots, K \end{aligned} \tag{8}$$

where $\mathcal{H}[n-1]$ denotes the true hypothesis in the $(n-1)$-th sensing interval. Note that the weights are updated only when $\mathcal{H}_1$ is the true hypothesis in the previous sensing interval. The weight of a user who made a wrong decision in the previous sensing interval is halved, while that of a user who made a correct decision does not change. The second equation in (8) makes the sum of the weights normalized to unity.

4 Numerical results

We compare the performance of the combining schemes in Section 3. The majority logic rule is considered for equal-weight combining, as suggested in [4]. For the optimal combining, we consider two cases: the ideal case when the fusion center knows all the required probabilities and the case when the counting method in [6] is applied to estimate the probabilities. The duration of $\mathcal{H}_1$ period and $\mathcal{H}_0$ period are assumed to follow geometric distribution with mean of 150 and 200 samples, respectively [7]. The number of accumulated samples L is fixed to 5. The number of secondary users K is set to 5, and the thresholds for local decisions are assumed to be the same for all the users.

Fig. 1 shows the receiver operating characteristic (ROC), when the channels between the primary user and secondary users are homogeneous; the

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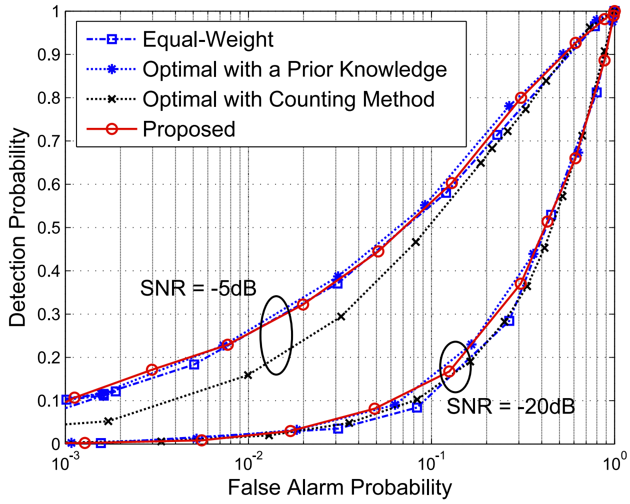

Fig. 1. ROC for a homogeneous channel.

long-term channels are the same for all the secondary users. When the average SNR = -20 dB, the performance is shown to be not much different for different schemes. When the average SNR = -5 dB, the proposed and equal-weight schemes are found to perform close to the optimum. The performance of the optimal scheme with counting method is relatively poor due to inaccurate estimation of probabilities.

Fig. 2 depicts the ROC curves, when the channels between the primary user and secondary users are heterogeneous. In particular, the secondary users are assumed to be uniformly located in a circle with the primary user being at the center. Unlike the homogeneous case, we observe significant performance disparity among combining schemes. The proposed scheme is shown to outperform the equal-weight scheme and optimal scheme with counting method, and surprisingly the performance is close to that of the optimal scheme with a prior knowledge.

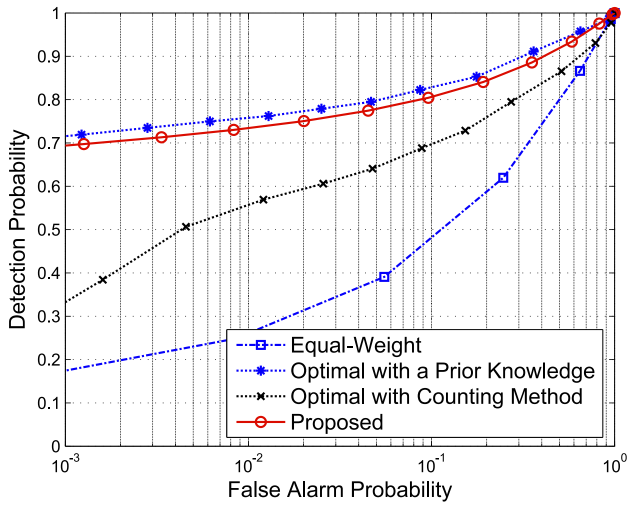

Fig. 2. ROC for a heterogeneous channel.

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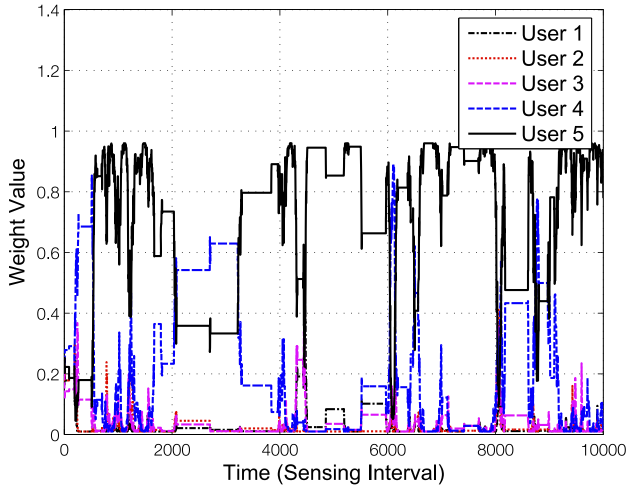

Fig. 3. Time variation of weight values of the proposed scheme.

Fig. 3 illustrates how the weights for the five users vary with time for the case of a heterogeneous channel, when the proposed scheme is adopted. The average SNR of each user is assumed to be 0 dB, 1 dB, 2 dB, 3 dB, and 4 dB, respectively. The weights are shown to change according to the channel condition. In particular, the weight for user 5 becomes small when the user is in deep fading, although the user has the highest SNR in the average. This is due to the inherent property that the proposed scheme adjusts the weights adaptively to the varying channel condition.

5 Conclusions

An adaptive combining scheme of hard decisions has been proposed for cooperative spectrum sensing in cognitive radio systems. The combining scheme effectively realizes unequal weighting based on the reliability estimates of the users. The proposed scheme is found to significantly outperform the equal-weight scheme. Furthermore, the proposed scheme is relatively easy to implement, since each user needs to report only one-bit hard decisions, and all the weights are updated at the fusion center without any a prior knowledge.

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