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A flexible cooperative spectrum sensing scheme for cognitive radio networks

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Abstract: In this paper, we propose a three-threshold decision based cooperative spectrum sensing algorithm (TTDCSS) with two rounds cooperation. Specifically, after the failure of the first cooperation, cognitive users begin to report the second local decision bit to the fusion center (FC) to perform a second cooperation, thus sensing failure is eliminated. Furthermore, by integrating uncertainty of noise variance, we propose a simple method to set local decision thresholds. Numerical results show that the TTDCSS algorithm is superior to the conventional double-threshold decision based sensing methods in the performance with a little increase of sensing bits.

Keywords: noise uncertainty, three-threshold, cooperative sensing, cognitive radio

Classification: Science and engineering for electronics

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1 Introduction

Cognitive radio is becoming an effective means to alleviate the scarcity of spectrum resources. To guarantee the service quality of the primary users (PUs) as well as the spectrum availability of the secondary users (SUs), quick and reliable detection of the spectrum holes is a challenging issue. However, detection performance is often comprised with multipath fading, shadowing and the noise uncertainty problems. Cooperative sensing is a competitive way to mitigate such impacts [1]. In particular, the SUs first send local sensing information to the FC and then the FC makes final decision by integrating the received information. Nevertheless, with the increasing of the SUs number, the information quantity reported to the FC become huge, even that the one-bit hard decision is reported. To avoid congestion on the reporting channel (also control channel), [2] proposed a double-threshold decision based cooperative spectrum sensing (DTDCSS) shceme which only permits the reliable users to send decision bits. However, sensing failure may frequently occur when there is only a few SUs.

In this paper, we propose a two-round cooperation spectrum sensing algorithm based on three-threshold local detection. Furthermore, a simple method to determine the local decision thresholds is proposed in light of the uncertainty of noise variance near the FC.

2 Double-Threshold Decision Based Cooperative Spectrum Sensing

For a large scale cognitive radio network, the total number of sensing bits transmitted to the FC tends to be very large and they will require a high demand in control channel bandwidth. The authors of [2] proposed a censored decision method to exclude ambiguous detection region, thus the sensing bits is greatly decreased. As shown in Fig. 1 (a), the SU reports a local decision as below:

$$D_k = \begin{cases} 0, & 0 \leq Y_k \leq \lambda_1 \\ no\ decision, & \lambda_1 < Y_k < \lambda_2 \\ 1, & Y_k \geq \lambda_2 \end{cases} \tag{1}$$

Where Y_k denotes the sensed energy at the kth SU. The normalized average number of sensing bits is defined as $\bar{K} = K_{avg}/N$ with average sensing bits

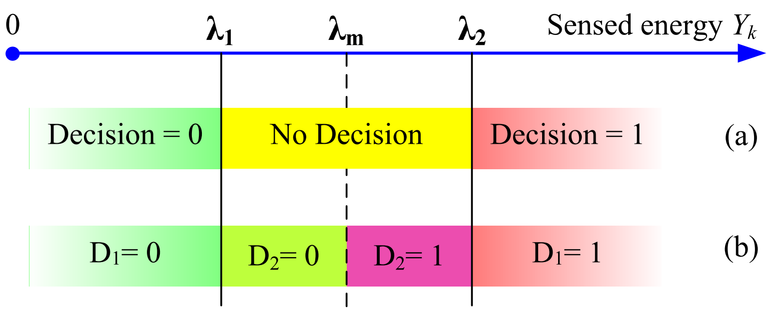

Fig. 1. Illustration of the local decision

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K_{avg} and SU number N. According to (6) of [2],

$$\bar{K}_{DTDCSS} = 1 - Prob\{\lambda_1 < Y_k < \lambda_2\} = 1 - P_0\Delta_0 - P_1\Delta_1 \tag{2}$$

where P_i denotes the absence probability ($i = 0$) or presence probability ($i = 1$) of the PU. The symbol Δ_i represents the probability that the statistics Y_k of all the SUs simultaneously fall in the interval of (λ_1, λ_2) under hypothesis $\mathcal{H}_i$.

Although the DTDCSS method can greatly reduce the capacity requirements on the control channel, it may face sensing failure when none of the SUs send decision information. According to [2], the probability of sensing failure is formulated as:

$$P_{sf} = P_0\Delta_0^N + P_1\Delta_1^N \tag{3}$$

When the number of SUs is quite large, the probability of sensing failure is negligible. However, when the number of SUs is very small, the sensing failure probability can not be ignored. For example, we consider the case that there is only a few SUs in the middle of the night, the cognitive users might miss certain access opportunity due to sensing failure. To sum up, the conventional double-threshold-decision based method is not flexible. In addition, the issue of how to determine the thresholds λ_1 and λ_2 is not addressed in the present literature concerned. In the next section, we propose a novel three-threshold decision based cooperative spectrum sensing method (TTDCSS) focusing on eliminating sensing failure, as well as determination of the decision thresholds.

3 Three-Threshold Decision Based Cooperative Spectrum Sensing

For simplicity of analysis, energy detector is considered in this study to perform local spectrum sensing while fusion rule "OR" is adopted in the FC, like [2]. We further assume that the reporting channel from the SUs to the FC has been established on a UWB channel or an unlicensed band such as ISM band [3], and the FC broadcasts the final result on regional beacons by a dedicated channel [4].

As shown in Fig. 1 (b), we propose to insert an intermediate threshold λ_m between λ_1 and λ_2. If the statistics Y_k is larger than λ_1 or less than λ_2, sensing strategy is the same as the conventional double-threshold method. However, if Y_k is within the interval (λ_1, λ_2), meanwhile the SU does not receive any final decision information from the FC by the end of the first cooperation, it implies that the first round sensing is failed. Then the SUs compare Y_k with λ_m, and send their decision results to the FC. Lastly, the FC makes the final decision by integrating the local decisions and broadcasts the result to the SUs.

Note that we assume the SUs can keep accurate synchronization with the FC. If the maximum transmission time of local information is assumed to be T_t and the fusion time T_f, then the excluded SUs begin to report decision bits

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after $T_t + T_f$ seconds unless they have received a fusion result. The TTDCSS algorithm is detailedly described as in Algorithm 1.

Algorithm 1 TTDCSS algorithm with two-round cooperation

For secondary users:

Begin
Perform local sensing and get Y_k
if $0 < Y_k \leq \lambda_1$ **then** $D_{k,1} = 0 \rightarrow FC$
else if $Y_k \geq \lambda_2$ **then**
  $D_{k,1} = 1 \rightarrow \mathrm{FC}$
else if $\lambda_1 < Y_k < \lambda_2$ **then**
  Start a timer with initial value $T_t + T_f$
  while Timer is not expired **do**
    Check the receiver
    if Receive the final decision **then**
      Go to the end
    end if
  end while
  if $Y_k < \lambda_m$ **then**
    $D_{k,2} = 0 \rightarrow \mathrm{FC}$
  else
    $D_{k,2} = 1 \rightarrow \mathrm{FC}$
  end if
end if
End

To determine the local decision thresholds, we first consider the single-threshold case. For simplicity, all the SU's local false alarm probabilities are assumed to be identical, namely $P_{f,k} = P_f$, the error probabilities of control channel are the same yet, i.e. $P_{e,k} = P_e$. Under the constraint of final false alarm probability $\bar{Q}_f$, the target false alarm probability of each of the SUs is given by [5]

$$\overline{P}_f = \frac{1 - \sqrt[N]{1 - \overline{Q}_f} - P_e}{1 - 2P_e}, \tag{4}$$

Assume that the uncertainty of noise near a cognitive base station is described as $[\sigma_n^2/\rho, \rho\sigma_n^2]$ [6], which can be acquired by historical observation. And σ_n^2 represents the average noise variance within the foot of the cognitive radio base station. It is also supposed that all the SUs normalize their sensed energy with the nominal variance σ_n^2. If one uses single-threshold to perform local decision, the SU who experiences noise with large variance will more likely make false alarm. On the contrary, the SU who undergoes noise with small variance may miss some access opportunity. Motivated by the double-threshold decision, we select the decision threshold corresponding to the maximum noise variance as the upper threshold λ_2, and select

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the decision threshold corresponding to the minimum noise variance as the lower threshold λ_1. The middle threshold λ_m can be determined by nominal variance σ_n^2.

It is well known that the sensed energy at the SUs follows chi-sqaure distribution under hypothesis $\mathcal{H}_0$ [7]. Suppose the kth SU experiences nominal variance noise, then $Y_k/\sigma_n^2 \sim \chi^2_{2TW}$ and the decision threshold λ_m should satisfy

$$\bar{P}_f = 1 - chi2cdf\left(\frac{\lambda_m}{\sigma_n^2}, 2TW\right), \tag{5}$$

therefore

$$\lambda_m = \sigma_n^2 \cdot chi2inv(1 - \bar{P}_f, 2TW), \tag{6}$$

where $chi2cdf(\lambda, v)$ and $chi2inv(p, v)$ denotes the CDF of chi-square distribution with freedom v and its inverse function, respectively. If the SU experiences noise with the maximum variance, i.e. $Y_k/\rho\sigma_n^2 \sim \chi^2_{2TW}$, the decision threshold λ_2 should satisfy

$$\bar{P}_f = 1 - chi2cdf\left(\frac{\lambda_2}{\rho\sigma_n^2}, 2TW\right), \tag{7}$$

and then

$$\lambda_2 = \rho\sigma_n^2 \cdot chi2inv(1 - \bar{P}_f, 2TW) = \rho\lambda_m, \tag{8}$$

Similarly, for the SUs who undergo noise of the minimum variance, the decision threshold λ_1 can be derived as follows

$$\lambda_1 = \frac{1}{\rho}\sigma_n^2 \cdot chi2inv(1 - \bar{P}_f, 2TW) = \frac{1}{\rho}\lambda_m, \tag{9}$$

4 Performance analysis

4.1 Cooperation overhead

We use normalized average sensing bits as the measurement of cooperation overhead like [2]. If one uses the double-threshold decision, the cooperation overhead is summarized as (2). Alternatively when the three-threshold local decision is utilized, the cooperation overhead will increase due to the second round cooperation. Assume that the average sensing bits in the first and the second cooperation are K_{avg1} and K_{avg2}, respectively. We get

$$K_{avg1} = N - P_0N\Delta_0 - P_1N\Delta_1, \tag{10}$$
$$K_{avg2} = P_0N\Delta_0^N + P_1N\Delta_1^N, \tag{11}$$

then

$$\begin{aligned} K_{avg} &= K_{avg1} + K_{avg2} \\ &= N - NP_0(\Delta_0 - \Delta_0^N) - NP_1(\Delta_1 - \Delta_1^N) \end{aligned} \tag{12}$$

The normalized average sensing bits of the proposed algorithm follows

$$\bar{K}_{TTDCSS} = 1 - P_0(\Delta_0 - \Delta_0^N) - P_1(\Delta_1 - \Delta_1^N) \tag{13}$$

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4.2 Sensing performance analysis

The proposed scheme integrates the single-threshold-decision based method and the double-threshold decision based method together. If the first round cooperation is successful, the sensing performance of TTDCSS is equivalent to that of the former. On the contrary, if the first round cooperation is failed, the sensing performance is equivalent to that of the latter. Assume that the false alarm probability and the miss alarm probability of the conventional single-threshold decision based cooperative spectrum sensing is $Q_{f,ST}$ and $Q_{m,ST}$, respectively. We also assume that the sensing performance of DTDCSS can be characterized by false alarm probability $Q_{f,DT}$ and miss alarm probability $Q_{m,DT}$. Then the false alarm probability and the miss alarm probability of TTDCSS are given by (14) and (15), respectively.

$$Q_{f,TTDCSS} = Q_{f,DT} - \Delta_0^N (1 - Q_{f,ST}) \tag{14}$$

$$Q_{m,TTDCSS} = Q_{m,DT} - \Delta_1^N (1 - Q_{m,ST}) \tag{15}$$

The second terms of (14) and (15) represent the performance gain attributed to the second round cooperation. The derivation of $Q_{f,DT}$, $Q_{m,DT}$, $Q_{f,ST}$ and $Q_{m,ST}$ is omitted due to space limit, which can be found in [2] and [8].

5 Numerical results

Figure 2 shows the relationship between normalized average sensing bits and noise uncertainty degree ρ. Suppose that there are 5, 20 and 50 SUs to participate in cooperative spectrum sensing. It can be seen that the TTDCSS dose not obviously increase average sensing bits. Although the normalized average sensing bits of TTDCSS is higher than DTDCSS under small N, the avergae sensing bits (calculated by $N\bar{K}$) is completely acceptable. Moreover, when the user number N gets large, e.g. $N = 50$, the normalized average sensing bits needed in the two schemes are almost the same. It can be

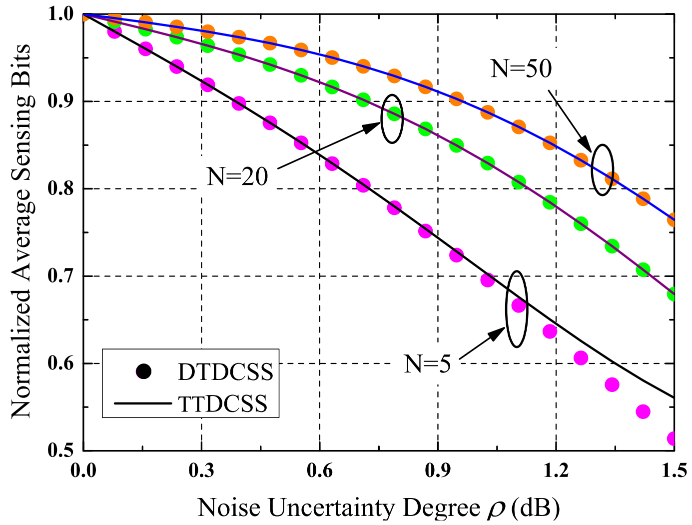

Fig. 2. Cooperation overhead comparison of various schemes for $SNR = 5\,\text{dB}$, $P_0 = P_1 = 0.5$, $P_e = 10^{-4}$ and $Q_f = 0.1$

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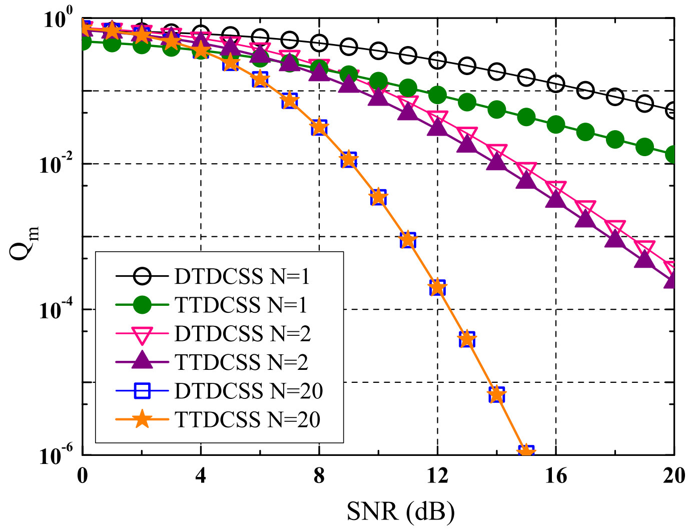

Fig. 3. Probability of miss alarm versus average SNR under $P_e = 10^{-4}$, $P_0 = P_1 = 0.5$ and $Q_f = 0.01$

interpreted that in such cases the probability of proceeding the second round cooperation is considerably low.

Figure 3 presents the miss alarm probability performance of the DTDCSS algorithm and the TTDCSS algorithm, for a given false alarm probability 0.01. The sensing channel is assumed to be Rayleigh fading channel with average SNR varying from 0 dB to 20 dB. The uncertainty degree of noise is set to 1 dB. We observe that miss alarm probabilities of the DTDCSS are distinctly higher than that of the TTDCSS owing to sensing failure when the user number is small. We also observe that the performance improvement of the TTDCSS is less obvious as the user's number increases. Since with large user number, the sensing-failure probability approaches to 0, and then the TTDCSS scheme is reduced to the DTDCSS scheme.

6 Conclusions

In this paper, we propose a flexible three-threshold decision based cooperative spectrum sensing (TTDCSS) scheme. Compared to the conventional double-threshold based sensing algorithm, the TTDCSS algorithm makes local decision by three thresholds. This algorithm does not need re-sensing after the first round cooperation failed, instead, it requires the SUs to send the second decision bits to the FC to perform another cooperation. So that the sensing failure is eliminated. Numerical results show that the TTDCSS algorithm can distinctly improve the sensing performance without obvious increase of average sensing bits.

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