Performance of DF Protocol for Distributed Cooperative Spectrum Sensing in Cognitive Radio

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ABSTRACT

Cognitive radio has been proposed to mitigate the spectrum scarcity problem by allowing the secondary users to access the under-utilized frequency bands and opportunistically transmit. Spectrum sensing, as a key technology in cognitive radio, is required to reliably detect the presence of primary users to avoid the harmful interference. However, it would be very hard to reliably detect the presence of primary users due to the channel fading, shadowing. In this paper, we proposed a distributed cooperative spectrum sensing scheme based on conventional DF (decode-and-forward) cooperative diversity protocol. We first consider the cooperation between two secondary users to illustrate that cooperation among secondary users can obviously increase the detection performance. We then compare the performance of DF based scheme with another conventional AF (amplify-and-forward) protocol based scheme. And it is found that the proposed scheme based on DF has a better detection performance than the one based on AF. After that, we extend the number of cooperative secondary users, and demonstrate that increasing the cooperation number can significantly improve the detection performance.

Key Words : Cognitive radio, Cooperative spectrum sensing, DF, Detection performance

I. Introduction

It is commonly believed that there is a spectrum scarcity at frequency bands that can be economically used for wireless communications. The actual measurements of 0-6 GHz spectrum utilization taken in downtown Berkeley are believed to be typical and indicate low utilization, expecially in the 3-6 MHz bands [1]. The Federal Communications Commission (FCC) reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85%, whereas only 2% of spectrum would be used in US at any given moment [2]. In order to utilize these spectrum 'white spaces', the FCC announced Cognitive Radio (CR) technology as a candidate to implement negotiated or opportunistic spectrum sharing [3].

As an important technology in cognitive radio, spectrum sensing needs to reliably detect the presence of primary users before secondary users access the frequency bands and vacate the bands as soon as primary users restart the transmission. However, as shown in [4] and [5], the detection performance would be compromised when secondary users are experiencing fading or shadowing effects, or the secondary user is in the boundary of decodability of the primary user, so that the received signal from the primary user is too weak to be detected. Thus secondary users may assume that the observed frequency bands are vacant and access to the bands while primary users are still in operation. Such scenario is not allowed in cognitive radio networks.

To address this issue, cooperative spectrum sensing is proposed in [1], [5] and [6]-[9] to improve the detection performance. In [1], authors showed that cooperative spectrum sensing can be implemented in

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two ways: centralized and distributed. In [5], based on energy detector, authors illustrated that through cooperation among secondary users, the detection probability is highly increased. In [6]-[9], authors introduced amplify-and-forward (AF) cooperative diversity protocol to cooperative spectrum sensing and showed that according to cooperation, the detection time was reduced and thus the overall agility was achieved. As mentioned above, these literatures

focused on the centralized cooperative spectrum sensing. In this paper, we propose a decode-and-forward (DF) cooperative diversity protocol based distributed cooperative spectrum sensing scheme under cooperation between two secondary users. Compared with AF protocol, the proposed scheme has a better detection performance. Then the multiple cooperation among secondary users is discussed.

The remainder of this paper is organized as follows. We introduce the cooperative spectrum sensing model in section Ⅱ. In section Ⅲ, the DF protocol based distributed cooperative spectrum sensing scheme is proposed. After that, we extend to the multiple cooperation scenario based on the proposed scheme in section Ⅳ. In section Ⅴ, the simulation results are presented. Finally, conclusions are drawn in section Ⅵ.

Ⅱ. System Model

In cognitive radio networks, secondary users are allowed to access the licensed frequency bands which are not occupied by primary users in some specific time and allocation. So it is required that the spectrum sensing of secondary users needs to accurately detect the presence of primary users.

As shown in Figure 1, there are two secondary users, S_1, S_2, and one primary user P_u in the cognitive radio network. One of the secondary users, S_1, is in the boundary of decodability of the primary user P_u. In the non-cooperative spectrum sensing, S_1 and S_2 will individually monitor the frequency band for detecting the existence of primary user P_u. As the special location of S_1, the received signal from primary user P_u will be so weak that it is hard for S_1 to differentiate whether the received signal is noise or the real

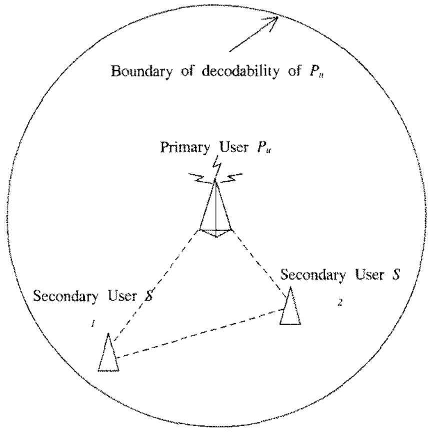

Fig. 1. Cooperative spectrum sensing.

transmitted signal from P_u. So there would be detection mistake that S_1 assume the absence of P in the frequency band and access the band to start its own transmission, which will bring harmful interference to primary user P_u.

In [1], three signal processing techniques for spectrum sensing which are used in traditional systems are discussed, matched filter, cyclostationary feature detector and energy detector. The optimal way for any signal detection is a matched filter which can maximize received signal-to-noise ratio. It requires secondary users to have a priori knowledge of primary users signal, such as modulation type and order, pulse shaping. It means: a secondary user must have a dedicated receiver to achieve synchrony with each different type of primary users. This coherent detector is very hard to be implemented. The cyclostationary feature detector can detect signals even that SNR is very low. But it also requires some prior knowledge of primary users. By comparison, although the energy detector is sub-optimal, it is non-coherent and can be simply implemented. So in this paper, we use energy detector in spectrum sensing.

Next, we formulate the spectrum sensing problem described above. In this paper, we assume that all channels experience Rayleigh fading. If there is no cooperation between any two secondary users, the received signal y_i at secondary user S_i is given by,

$$y_i = \theta h_{pi} + n_i \tag{1}$$

where h_{pi} is the instantaneous channel gain between the primary user P_u and i_{th} secondary user; n_i is the additive noise for i_{th} secondary user; h_{pi} and n_i are both modeled as independent complex Gaussian random variables with zero-mean; for simplicity, the noise in this paper is assumed to be of zero-mean and unit-variance; θ denotes the primary user indicator, $\theta=1$ implies presence of the primary user and $\theta=0$ implies the primary user's absence.

In energy detector, the formed statistics is given by,

$$Y_i = |y_i|^2 \tag{2}$$

and this statistics Y_i will be compared with a threshold λ, where if $Y_i > \lambda$, the primary user P_u is declared to be present in the frequency band, otherwise, P_u is declared to be absent, which can be described as follows,

$$\begin{cases} Y_i > \lambda : H_1(\theta=1) \\ Y_i < \lambda : H_0(\theta=0) \end{cases} \tag{3}$$

where two hypotheses H_1 and H_0 stand for $\theta=1$ and $\theta=0$ respectively. So the expected value of Y_i can be calculated as,

$$E(Y_i) = \begin{cases} 1, & H_0 \\ P_i+1, & H_1 \end{cases} \tag{4}$$

where $P_i = E\{|h_{pi}|^2\}$ refers to the received signal power at S_i from primary user P_u. Obviously, Y_i is exponentially distributed. Then the probability of false alarm and the probability of detection can be derived as,

$$P_f = P_r(Y_i > \lambda | H_0) = e^{-\lambda} \tag{5}$$

$$P_d = P_r(Y_i > \lambda | H_1) = e^{-\frac{\lambda}{P_i+1}} \tag{6}$$

From (5) and (6), for a given probability of false alarm, we can get the detection probability. In Figure 2, we have plotted the detection probability versus the false alarm probability under non-cooperation scenario. We can see that increasing the value of P_i will improve the detection performance, where P_i stands for the received signal power from primary user P_u. On the contrary, if some secondary users are far away from the primary user, then the received signal power for these secondary users will be very weak,

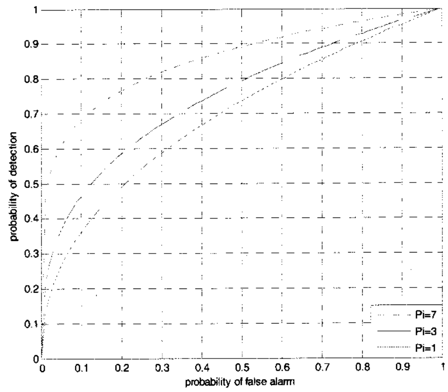

Fig. 2. Pd vs. Pf without cooperation.

thus the detection performance is poor. So as shown in Fig. 1, due to the location of S_1, the detection performance of S_1 is too bad to reliably detect the primary user P_u. So in this paper, we apply cooperative spectrum sensing among secondary users, and we will show that according to cooperation, the detection performance can be improved.

As shown in [1], two schemes can be used in cooperative spectrum sensing, distributed scheme and centralized scheme. In centralized cooperative spectrum sensing, secondary users first perform local spectrum sensing individually, then forward the observations or the binary decisions to a common receiver which may be an access point in a wireless LAN or a base station in a cellular network . The common receiver combines these decisions or observations and makes a final decision to infer the presence or absence of the primary user in the observed frequency band. In distributed cooperative spectrum sensing, secondary users perform the spectrum sensing individually, but they are allowed to communicate with each other and exchange their information. The distributed cooperation scheme may be easier to implement where the neighbours are chosen randomly [1]. So, in this paper, we utilize distributed cooperation scheme.

We assume that distributed cooperative spectrum sensing is under a fixed TDMA mode with orthogonal transmission. As shown in Figure 3, in time slot T_1, S_1 and S_2 perform the spectrum sensing individually.

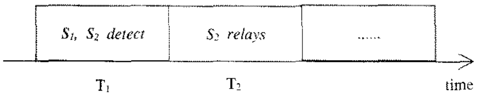

Fig. 3. TDMA mode.

Based on the distributed cooperation scheme, in time slot T_2, S_2 relays the data to S_1 which is received from P_u in time slot T_1.

Ⅲ. Distributed Cooperative Spectrum Sensing

In section II, we have shown that if there is no cooperation among secondary users, the detection performance would be degraded when the received signal from primary user is weak. In [6]-[9], authors discussed centralized cooperative spectrum sensing based on AF cooperative diversity protocol. As we know, there is another conventional protocol, DF. We will apply DF protocol in distributed cooperative spectrum sensing and compare the performance of AF and DF. So in this section, we will formulate the distributed cooperative spectrum sensing problem based on the DF protocol.

As shown in Fig. 3, in time slot T_1, S_1 and S_2 will perform the spectrum sensing individually, according to (1), the received signals at S_1 and S_2 are,

$$y_1 = \theta h_{p1} + n_1 \quad (7)$$

$$y_2 = \theta h_{p2} + n_2 \quad (8)$$

In time slot T_2, S_2 relays the data received in time slot T_1 to S_1. We assume that S_2 applies DF protocol to process the data received from P_u, S_2 will first decode the received signal, then re-encode it, and retransmit the new encoded signal to S_1. According to [10], decoding at the relay can take on a variety of forms: the relay might fully decode, i.e., estimate without error; or it might employ symbol-by-symbol decoding and allow the destination to perform full decoding. In this paper, we apply fully decoding for balancing performance and complexity at the relay S_2. During the relay time slot T_2, the signal received at S_1 from the relay S_2 under DF protocol is defined as,

$$y_1 = \theta h_{12} + n_{12} \quad (9)$$

where θ is the signal decoded, re-encoded and retransmitted by relay S_2; n_{12} denotes the noise when S_1 is receiving the relayed data from S_2; h_{12} is the instantaneous channel gain between secondary user between S_1 and S_2,modeled as a Guanssian random variable with zero mean. Thus, after combining the received data in time slot T_1, the received signal at S_1 is given by,

$$y_1 = (h_{p1} + h_{12})\theta + (n_1 + n_{12}) \quad (10)$$

so, in the energy detector of S_1, the formed statistics is $Y_1 = |y_1|^2$, the expected value of Y_1 under two hypotheses H_0, H_1 is as follows:

Case 1 (H_0): when $\theta = 0$, the primary user P_u is absent in the frequency band, so the expected value of Y_1 is,

$$E(Y_1|H_0) = 2 \quad (11)$$

then we can derive the probability of false alarm P_f,

$$\begin{aligned} P_f &= P_r(Y_1 > \lambda|H_0) \\ &= \int_\lambda^\infty \frac{1}{2} e^{-\frac{y}{2}} dy \\ &= e^{-\frac{\lambda}{2}} \end{aligned} \quad (12)$$

Case 2 (H_1): when $\theta = 1$, the primary user P_u is present in the frequency band, so the expected value of Y_1 is,

$$E(Y_1|H_1) = P_1 + P_{12} + 2 \quad (13)$$

thus the probability of detection, P_d, is calculated as,

$$\begin{aligned} P_d &= P_r(Y_1 > \lambda|H_1) \\ &= \int_\lambda^\infty \frac{1}{P_1 + P_{12} + 2} e^{-\frac{y}{P_1 + P_{12} + 2}} dy \\ &= e^{-\frac{\lambda}{P_1 + P_{12} + 2}} \end{aligned} \quad (14)$$

where $P_{12} = E\{|h_{12}|^2\}$ refers to the channel gain between the secondary user S_1 and S_2.

According to [6], the false alarm probability and detection probability under AF protocol is given, respectively,

$$P_f = \phi(\lambda;1,1) \quad (15)$$

$$P_d = \phi(\lambda; P_1 + 1, P_2 + 1) \quad (16)$$

where

$$\phi(\lambda; x, y) = \int_0^{\infty} e^{-z - \frac{\lambda}{x + yz}} dz \quad (17)$$

So, from (12), (14), (15) and (16), for a given probability of false alarm, we can get the detection probability under DF and AF, respectively.

Ⅳ. Cooperative Spectrum Sensing among Multiple Users

In section III, we discussed the DF diversity protocol based cooperative spectrum sensing between two secondary users, S_1 and S_2. In this section, we will extend the number of cooperation users, i.e., S_1 will have more than one secondary user acting as a relay.

Suppose that there are N secondary users in the cognitive radio network, including S_1 and another $N-1$ secondary users which relay the data to S_1. In time slot T_1, those N secondary users perform the spectrum sensing individually. In time slot T_2, $N-1$ secondary users relay the received data in the previous time slot to S_1. Thus, after combining the data received in time slot T_1, the received signal at S_1 is given by,

$$y_1 = \theta(h_{p1} + \sum_{i=2}^{N} h_{1i}) + (n_1 + \sum_{i=2}^{N} n_{1i}) \quad (18)$$

For simplicity, we assume that these N secondary users are experiencing the independent and identical channel fading; n_{1i} denotes the noise when S_1 is receiving the relayed data from ith relay; h_{1i} is the instantaneous channel gain between secondary user S_1 and the ith relay. Thus $Y_1 = |y_1|^2$ is following the chi-square distribution, instead of exponential distribution, i.e.,

$$Y_1 \sim \begin{cases} \chi_k^2, & H_0 \\ \chi_k^2(\gamma), & H_1 \end{cases} \quad (19)$$

and the pdf of Y_1 is given as follows,

$$f_k(y) = \begin{cases} \frac{(1/2)^{k/2}}{\Gamma(k/2)} y^{k/2-1} e^{-y/2}, & H_0 \\ \frac{1}{2} e^{-(y+\gamma)/2} (\frac{y}{\gamma})^{k/4-1/2} I_{k/2-1}(\sqrt{\gamma y}), & H_1 \end{cases} \quad (20)$$

where k is the degree of freedom; γ is the non-centrality parameter, defined as the instantaneous signal-to-noise ratio [5]; $I_{k/2-1}(\cdot)$ is the modified Bessel function of the first kind with $(k/2-1)$th order; $\Gamma(.)$ is the complete gamma function defined by,

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \quad (21)$$

so when $\theta = 0$, the same as section III, we can get the expected value of Y_1 as,

$$E(Y_1 | H_0) = N \quad (22)$$

then the false alarm probability can be calculated as,

$$\begin{aligned} P_f &= P_r(Y_1 > \lambda | H_0) \\ &= \int_{\lambda}^{\infty} f_k(y) dy \\ &= \int_{\lambda}^{\infty} \frac{(1/2)^{N/2}}{\Gamma(N/2)} y^{N/2-1} e^{-y/2} dy \end{aligned} \quad (23)$$

when $\theta = 1$, the expected value of $Y_1 = |y_1|^2$ is changed to,

$$E(Y_1 | H_1) = P_1 + (N-1)P_{12} + N \quad (24)$$

thus, we can derive the detection probability,

$$\begin{aligned} P_d &= P_r(Y_1 > \lambda | H_1) \\ &= \int_{\lambda}^{\infty} f_k(y) dy \\ &= \int_{\lambda}^{\infty} \frac{1}{2} e^{-(y+P_{12})/2} (\frac{y}{P_{12}})^{\frac{P_1+(N-2)P_{12}+N}{4} - \frac{1}{2}} \\ &\quad \cdot I_{\frac{P_1+(N-2)P_{12}+N}{2} - 1}(\sqrt{P_{12} y}) dy \end{aligned} \quad (25)$$

Thus, from (23), (25), we can obtain the detection performance for S_1 cooperating with multiple secondary users.

Ⅴ. Simulation Results

In this section, we first present the simulation results for the proposed DF based distributed cooperative spectrum sensing scheme. Then, the performance of cooperative spectrum sensing based on the proposed scheme among multiple users is given.

Figure 4 and Figure 5 show the performance of the proposed DF based scheme. In Figure 4, setting $P_f=0.1$, we have plotted the detection probability versus P_{12}, for three different values of P_1: $P_1=0dB$, $P_1=4dB$, $P_1=6dB$. For comparison, we also plotted the performance under non-cooperation scenario. The detection performance is getting improved when the cooperative spectrum sensing is applied among secondary users, but only for a certain range of P_{12}. When P_{12} is very small, the distance between S_1 and S_2 is so far that it is useless for S_1 to cooperate with such secondary user. So there exists a cooperating circle

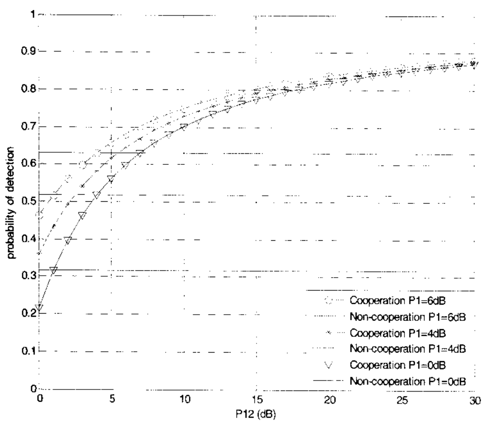

Fig. 4. P_d vs. P_{12}. Detection performance under DF with different value of P_1

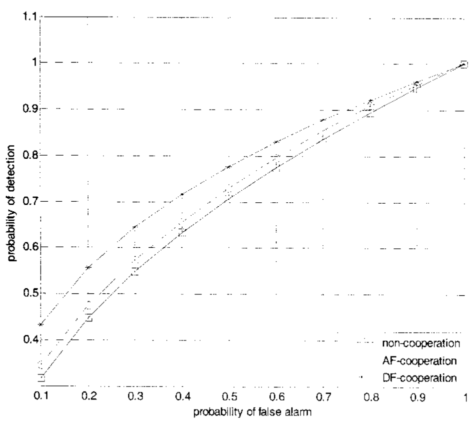

Fig. 5. P_d vs. P_f. Detection performance comparison under DF, AF and non-cooperation

around S_1 where those secondary users in this circle are qualified to act as a relay for S_1. And, apparently, cooperating with the nearby secondary user, i.e., P_{12} is larger, a higher detection probability can be achieved. We also note that when $P_{12}=30dB$, the detection performance under three different values of P_1 is almost the same. As discussed before, if P_1 is large, then the secondadry user S_1 is close to the primary user P_u, so a good detection performance can be obtained. Thus, if the cooperative secondary user S_2 is reliable enough, i.e., P_{12} is large , S_1 can achieve almost the same detection performance with the one which is close to the primary user P_u. The cooperation among secondary users is apparently beneficial.

In Figure 5, setting $P_1=1dB$, $P_2=2.5dB$, $P_{12}=2.5dB$, we have plotted the detection probability versus the false alarm probability under DF, AF based cooperative spectrum sensing scheme and without cooperation scenario for comparison. We note that both cooperative spectrum sensing schemes based on DF and AF have a higher detection probability than the non-cooperative spectrum sensing scheme. So, apparently, no matter which diversity protocol is used in cooperative spectrum sensing, allowing cooperation among secondary users can improve the detection performance. From Figure. 4, we have noted that based on DF protocol, when the secondary user S_2, which acting as a relay, is more closer to S_1, i.e., P_{12} is larger, the detection performance is much better. In Figure 5, even we set $P_{12}=2.5dB$, a small value, which denotes not a good detection performance based on DF protocol, the proposed scheme based on DF still has much better performance than the scheme based on AF protocol, where almost more than 10% higher detection probability is achieved.

Considering the cooperative spectrum sensing among multiple users, we have plotted the detection probability versus the false alarm probability in Figure 6, setting $P_1=1dB$, $P_{12}=2.5dB$. From Figure 6, we can obviously get that when the number of cooperative secondary users is increased, i.e., N is becoming larger, the detection probability for S_1 is apparently enlarged. When the false alarm probability is small, such as 0.1, cooperating with 8 secondary users ($N=9$), S_1 can achieve almost 30% higher detection

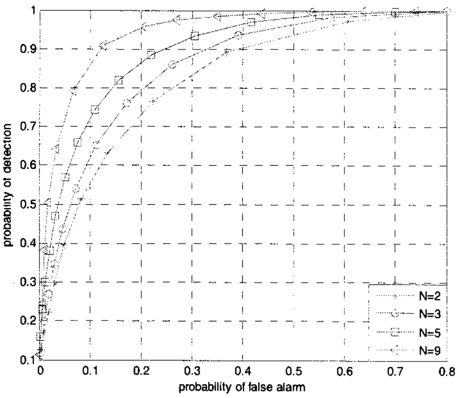

Fig. 6. P_d vs. P_f. Detection performance with multiple cooperation secondary users

probability compared to cooperating with only one secondary user ($N=2$).

Ⅵ. Conclusions

In this paper, we exploit a distributed cooperative spectrum sensing scheme based on DF cooperative diversity protocol, where one secondary user is hard to detect the presence of the primary user in the frequency band, due to its special location in the boundary of decodability of the primary user. We first derive the formulation of the proposed scheme where only two secondary users are applying cooperative spectrum sensing. We make a detection performance comparison with the scheme under DF and AF diversity protocol, respectively. We illustrate that the proposed scheme based on DF protocol has a better detection performance than the scheme based on AF protocol. Then, based on the proposed DF based scheme, we extend the number of cooperative secondary users. It is proved that allowing more secondary users cooperating with each other can apparently improve the detection performance.

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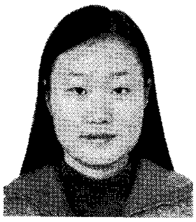

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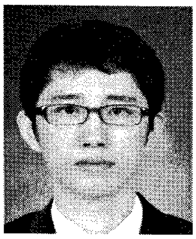

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