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Comparison of DF and AF Based Cooperative Spectrum Sensing in Cognitive Radio

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Abstract-**In cognitive radio networks, secondary users are allowed to access the under-utilized spectrum and opportunistically transmit whenever no primary signals are detected. So these unlicensed users need to monitor spectrum accurately to detect the presence of the licensed users. In this paper, we exploit a cooperative spectrum sensing between two secondary users to improve the detection performance when one of the users is standing in the decodability boundary of the primary user, which is difficult to detect the presence of this licensed user. We develop this cooperative spectrum sensing with decode- and-forward (DF) diversity protocol, and study the detection probability and outage probability to compare the performance of DF and amplify-and-forward (AF) protocols. We illustrate that DF protocol has better performance than AF in detection probability, contrarily, AF is better than DF in outage probability.**

I. INTRODUCTION

It is commonly believed that there is a spectrum scarcity at frequencies 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, especially in the 3-6 MHz bands. The FCC reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85%. 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 [1].

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment, and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real-time [2]. In the Cognitive radio network, secondary users (unlicensed) are allowed to use the licensed spectrums when primary users are absent in a specific time and allocation. Secondary users should make sure that they will not take any interference to primary users. So if secondary users can not reliably detect the presence of the primary users, they will assume that the observed channels are vacant and begin to access these channels while the primary users are still in operation. Hence, secondary users have to accurately monitor spectrum for the presence of primary users. However, as shown in [3], if one of the secondary users is in the boundary of decodability of the primary user, the detection for the presence of primary user will be degraded. In [1], the cooperative spectrum sensing is proposed to alleviate the problem of detecting primary users. It is shown that a large network of cognitive radios with sensing information exchanged between neighbors would have a better chance of detecting primary users compared to individual sensing. In [4], the authors proposed collaborative spectrum sensing in a group of secondary users to improve spectrum sensing performance when a secondary user experiences shadowing or fading effects. In [5]-[8], another kind of cooperative spectrum sensing under the AF diversity protocol was proposed. The authors first considered the cooperation between two secondary users, assuming one of the users to be a relay for another one which is in the boundary of decodability of the primary user, and discussed the detection probability and agility gain improvement. Then they extended to multi-user multi-carrier cognitive networks. In this paper, we exploit the cooperative spectrum sensing with DF diversity protocol between two secondary users, and make a comparison with AF protocol in terms of detection probability and outage probability.

Remainder of this paper is organized as follows. In section Ⅱ, we will give a description of spectrum sensing problem in cognitive radio networks. In section Ⅲ, the formulation of problem is described. We illustrate the performance of DF and AF diversity protocols in terms of detection probability and outage probability in section Ⅳ. In section Ⅴ, we present our conclusion.

II. DESCRIPTION OF SPECTRUM SENSING PROBLEM

Now we will describe the sensing problem in cognitive radio networks. As shown in Figure 1, there are two secondary users, S1, S2, and S1 is far away from the primary user P standing in the boundary of decodability of this primary user. S1 and S2 monitor the spectrums continuously and independently for the presence of P, report their detection results to a common receiver. In such a case, the signal received from primary user P is so weak for the secondary user S1 that S1 will be very difficult to detect the presence of the primary user. And this detection probability can be worse due to shadowing and fading effects. In this paper, we apply the cooperation between these two secondary users. The secondary user S2 which is more nearer to primary user P will act as a relay for S1 which is far away from P.

In [9] and [10], the authors proposed cooperative schemes with orthogonal transmission in a TDMA system. We assume that cooperative spectrum sensing is under a fixed TDMA mode. As shown in Figure 2, in time slot T1, S1 and S2 detect the primary user P individually. In time slot T2, S2 relays the data to S1, which is received from P in the previous time slot.

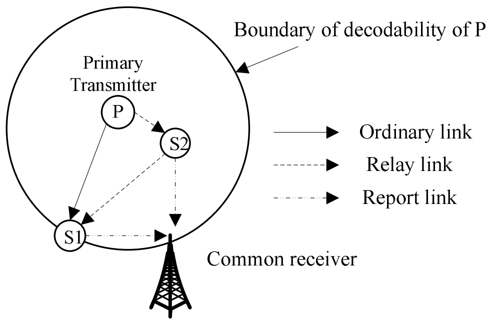

Fig. 1 Cooperative spectrum sensing.

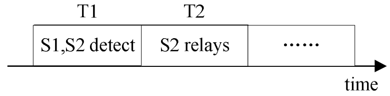

Fig. 2 TDMA mode.

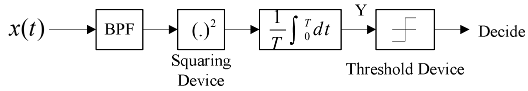

Fig. 3 Energy detector.

Three signal processing techniques for spectrum sensing which are used in traditional systems are discussed in [1], matched filter, energy detector and cyclostationary feature detector. The optimal way for any signal detection is a matched filter which can maximize received signal-to-noise ratio [12]. It requires that secondary users need to have a priori knowledge of primary users signal, such as modulation type and order, pulse shaping. So this 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. We choose energy detector to do signal processing for cooperative spectrum sensing. Figure 3 is the block diagram of an energy detector [11]. The band-pass filter is used to limit the bandwidth of input signal. It is followed by a squaring device used to measure the received energy and the integrator determining observation interval *T*. After the integrator is a threshold device, comparing the output of integrator *Y* with a threshold λ to decide if signal is present.

III. SYSTEM MODEL

In this section, we will formulate the cooperative spectrum sensing between two secondary users based on DF and AF diversity protocols.

We assume that all the users are experiencing Rayleigh fading, which is independent between every two users. The signal sent from one transmitter is *x*, and then the received signal at the receiver is *y*, defined as

$$y = ax + n$$

where *a* is the fading coefficient, *n* is the additive noise. *a* and *n* are both modeled as complex Gaussian random variables with zero-mean; the mean and variance of the noise are set to be zero and one, respectively.

A. DF Protocol

As shown in Figure 2, in time slot T1, S1 and S2 will detect the primary user P individually. We define the received data by S1 and S2 as,

$$y_1 = \theta a_1 + n_1$$
$$y_2 = \theta a_2 + n_2$$

where a_i is the instantaneous channel gain between the primary user and i_{th} secondary user; n_i is additive noise for secondary user s_i ; θ indicates the presence of the primary user, $\theta = 1$ implies the presence of the primary user, $\theta = 0$ implies the absence of the primary user.

In time slot T2, S2 relays the information received in time slot T1 to S1. We assume that the relay S2 uses decode- and-forward (DF) protocol which can achieve diversity gain to process the signal received from P. S2 will first decode the received signal, then re-encode it, and retransmit the new encoded signal to S1. According to [9], decoding at the relay can take on a variety of forms: the relay might full decode, i.e., estimate without error; or it might employ symbol-by-symbol decoding and allow the destination to perform full decoding. We apply fully decode for balancing performance and complexity at the relay. During the relay time slot T2, the signal received by S1 from the relay S2 under DF protocol is defined as

$$y_1 = \theta a_{12} + n_1$$

where θ is the signal decoded, re-encoded and retransmitted by relay S2; a_{ij} is the instantaneous channel gain between secondary user s_i and s_j. Combining the received data in time slot T1, the signal received by S1 is

$$y_1 = (a_{12} + a_1)\theta + n_1 \quad (1)$$

for simplicity, we rewrite the signal as

$$Y = A\theta + N \quad (2)$$

where *Y* implies the received signal y_1, $A=a_{12}+a_1$, and $N=n_1$. As we mentioned before, *a* and *n* are both complex Gaussian random variables with zero-mean, so *A* and *N* in (2) are complex Gaussian distributed with zero-mean and variances,

$$\begin{cases} \sigma_A^2 = A_1 + A_{12} \\ \sigma_N^2 = 1 \end{cases} \quad (3)$$

where

$$A_1 = E\left\{|a_1|^2\right\}$$

refers to the received signal power at secondary user S1 from primary user P. And

$$A_{12} = E\left\{|a_{12}|^2\right\}$$

refers to the received signal power at secondary user S1 from relay S2.

As shown in Figure 3, the output of integrator *Y* in the energy detector forms the statistics

$$T(Y) = |Y|^2 \quad (4)$$

B. AF Protocol

Under AF protocol, at the relay S2, the signal received from P is just amplified with a scaling factor β, and then transmitted to S1. According to [5], the same with DF protocol except that, in (2), A and N are changed to $A = \sqrt{\beta}a_{12}a_2 + a_1$, $N = n_1 + \sqrt{\beta}a_{12}n_2$; (3) is changed to

$$\begin{cases} \sigma_A^2 = A_1 + A_2 a \\ \sigma_N^2 = 1 + a \end{cases}$$

where $a = |a_{12}|^2 / E[|a_{12}|^2]$; $A_2 = E\{|a_2|^2\}$, refers to the received signal power at secondary user S2 from primary user P.

IV. Performance Comparison of DF and AF

In this section, we will discuss the performance of DF and AF in terms of detection probability and outage probability.

A. Detection Probability

As discussed in section III, the energy detector forms a statistics *T(Y)*. Since *A* and *N* are both complex Gaussian distribution, then *Y* given *A* is complex Gaussian. So it is obvious that *T(Y)* given *A* is exponential. We use $F_i(t)$ to denote the cumulative density function (cdf) of the statistics *T(Y)*, where $i=0,1$ implies $\theta=0,1$ (i.e. absence or presence of P).

i).DF Protocol:

Case 1: When P is absent in the spectrum, $\theta=0$, then from (2), *Y* is changed to

$$Y = N$$

and from (4)

$$T(Y) = |N|^2$$

so, we can get

$$E[T(Y)|\theta = 0] = E[|N|^2] = 1$$

then the cdf statistics *T(Y)*, $F_0(t)$is defined as

$$\begin{aligned} F_0(t) &= P[T(Y) > t|\theta = 0] \\ &= \int_t^\infty f(t)dt \\ &= e^{-t} \end{aligned}$$

Case 2: When P is present in the spectrum, $\theta=1$, similar to case 1, *Y* is changed to

$$Y = A + N$$

and

$$T(Y) = |A|^2 + |N|^2$$

so, we can get

$$E[T(Y)|\theta = 1] = A_1 + A_{12} + 1$$

then $F_1(t)$ is

$$\begin{aligned} F_1(t) &= P[T(Y) > t|\theta = 1] \\ &= \int_t^\infty f(t)dt \\ &= e^{-\frac{t}{A_1 + A_{12} + 1}} \end{aligned}$$

According to Figure 3, we need to find the threshold λ. We define λ for a given probability of false alarm α to be satisfied

$$F_0(\lambda) = \alpha$$

so the detection probability of S1 with cooperation of S2 is defined as

$$P_c = F_1(\lambda)$$

ii).AF Protocol:

The same with DF protocol, according to [5], define a function

$$\varphi(t; m, n) = \int_0^\infty e^{-a - \frac{t}{m + na}} da$$

then

$$F_0(t) = \varphi(t; 1, 1)$$

and

$$F_1(t) = \varphi(t; A_1 + 1, A_2 + 1)$$

so the detection probability of S1 with cooperation of S2 is

$$P_c = \varphi(\lambda; A_1 + 1, A_2 + 1)$$

where λ is satisfied

$$\varphi(\lambda; 1, 1) = \alpha$$

iii).Simulation Result:

According to the formulation discussed above, we set $A_1=1$, $A_2=2.5$, $A_{12}=1$ in the simulation. As seen in Fig. 4, the detection performance of DF protocol is better than AF. When the false alarm is low, the detection probability of DF protocol is 10% higher than AF. As we discussed in section III, the signal received from P at relay S2 is fully decoded, re-encoded and then transmitted to S1, during which the effect of noise is removed. That is why using DF protocol in the relay can get a better detection probability than AF.

B. Outage Probability

The cooperative spectrum sensing between two secondary users discussed in this paper can be modeled as a relay scheme in Fig. 5. The primary user P is acting as a source, secondary user S1 is the destination, S2 is the relay for S1.

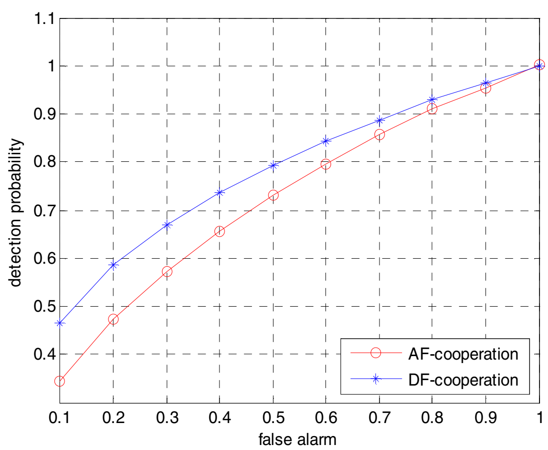

Fig. 4 Detection probability comparison with DF and AF.

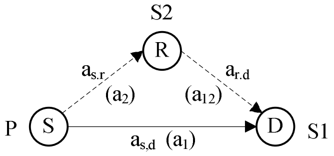

Fig. 5 Relay scheme.

According to [9], the outage probability of AF and DF diversity protocols satisfy, respectively,

$$p_{out}^{AF} \approx \left(\frac{1}{2\sigma_{s,d}^2} \cdot \frac{\sigma_{s,r}^2 + \sigma_{r,d}^2}{\sigma_{s,r}^2 \cdot \sigma_{r,d}^2}\right) \cdot \left(\frac{2^{2R}-1}{SNR}\right)^2 \quad (5)$$

$$p_{out}^{DF} \approx \frac{1}{\sigma_{s,r}^2} \cdot \frac{2^{2R}-1}{SNR} \quad (6)$$

where SNR is the signal-to-noise ratio of received data from source, mainly depending on the source's transmitted power; R is the spectral efficiency; $\sigma_{i,j}^{-2}$ is distribution parameter of fading coefficients $|a_{i,j}|^2$. In this paper, a is modeled as a complex Gaussian random variable, so $|a|^2$ is exponentially distributed with mean σ^2, where

$$\sigma_{s,d}^2 = A_1,\ \sigma_{s,r}^2 = A_2,\ \sigma_{r,d}^2 = A_{12}$$

so (5) and (6) are changed to

$$p_{out}^{AF} \approx \left(\frac{1}{2A_1} \cdot \frac{A_2 + A_{12}}{A_2 A_{12}}\right) \cdot \left(\frac{2^{2R}-1}{SNR}\right)^2$$

$$p_{out}^{DF} \approx \frac{1}{A_2} \cdot \frac{2^{2R}-1}{SNR}$$

According to the formulation, we set $A_1=1,\ A_2=2.5,\ A_{12}=1,\ R=0.52$ and get the simulation result in Fig. 6. Absolutely, the outage probability of DF protocol is much higher than AF. After $SNR=16dB$, the outage probability of DF is more than 10 times over AF. Taking detection probability into account, although DF protocol has better detection probability than AF, at the same target of outage probability, the required SNR of DF is correspondingly higher than AF, which means that applying AF protocol can detect more weak primary users.

V. Conclusion

In this paper, we exploited a cooperative spectrum sensing between two secondary users based on DF diversity protocol, in which one secondary user is hard to detect the presence of the primary user due to its location in the boundary of decodability of this primary user, and compared the performance of DF and AF in terms of detection probability and outage probability. We illustrated that although DF protocol has better detection ability than AF, at the same target of outage probability, the required SNR of DF is correspondingly higher than AF.

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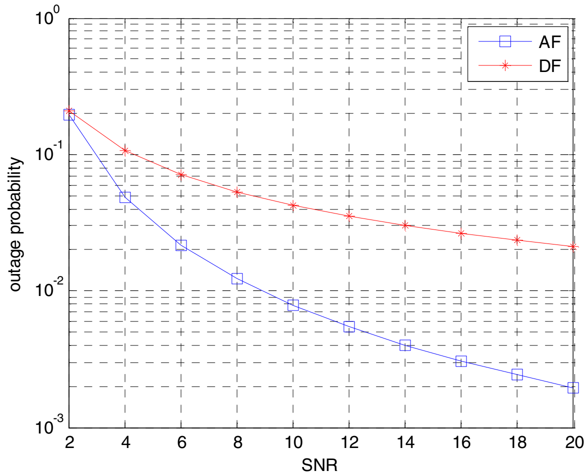

Fig. 6 Outage probability comparison with DF and AF.

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