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Performance Analysis of Cooperative Spectrum Sensing in Cognitive Radio

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ABSTRACT: Cognitive radio is a new and exciting technology that, among other applications, has the potential to unlock the spectrum necessary for the deployment of next generation high data rate systems. Spectrum sensing is the key component of cognitive radio technology. However, detection is compromised when a user experiences shadowing or fading effects. In such cases, user cannot distinguish between an unused band and a deep fade. Thus, cooperative spectrum sensing is proposed to optimize the sensing performance. We have studied performance analysis of cooperative spectrum sensing in Cognitive Radio. This paper presents a simulation comparison of cooperative with non-cooperative spectrum sensing over Rayleigh fading channel based on AND, OR and MAJORITY rules. Comparing the non-cooperative curve with the cooperative curve over Rayleigh fading channel, we observed that spectrum sensing is better in presence of cooperation. We also observed that the OR rule has the better performance than AND and MAJORITY rule.

KEYWORDS: cognitive radio, fusion rules, cooperative spectrum sensing, fading channels, energy detection.

1 INTRODUCTION

Cognitive radio (CR) enables much higher spectrum efficiency by dynamic spectrum access [1], [2]. Therefore, it is a potential technique for future wireless communications to mitigate the spectrum scarcity issue. As unlicensed (secondary) users of the spectrum band, CR operators are allowed to utilize the spectral resources only when it does not cause interference to the primary (licensed) users, which entails continuous spectrum sensing in CR networks. Therefore, it becomes a critical issue in cognitive radio to reliably and quickly detect the presence of the primary users. The existing spectrum sensing techniques can be broadly divided into three categories [3]: energy detection, matched filter detection, and cyclostationary detection. Among them, energy detection has been widely applied since it does not require any prior knowledge of the primary signals and has much lower complexity than the other two schemes. Therefore, we only consider energy detection for spectrum sensing throughout this letter. Spectrum sensing is a tough task because of shadowing, fading, and time-varying natures of wireless channels. To combat these impacts, cooperative spectrum sensing schemes have been proposed to obtain the spatial diversity in multiuser CR networks [4-6]. The performance of single CR user based spectrum sensing in fading channels such as Rayleigh, Nakagami, Weibull has been studied in [7]. In cooperative spectrum sensing, all CR users sense the PU individually and send their sensing information in the form of 1-bit binary decisions (1 or 0) to Fusion center (FC). The hard decision combining rule (OR, AND, and MAJORITY rule) is performed at FC using a counting rule to make the final decision regarding whether the primary user present or not [8]-[13]. In this paper, we have studied cooperative spectrum sensing over Rayleigh fading channel.

The rest of this paper is organized as follows. In Section II, the system model is introduced. In Section III, detection and false alarm probabilities of non-fading AWGN and Rayleigh fading channel is described. Cooperative spectrum sensing over Rayleigh fading channel is derived in Section IV. The simulation result and discussion are presented in section V. Finally, we draw our conclusion in Section VI.

2 SYSTEM MODEL

We assume that energy detection [14] is applied at each CR user (fig.1). The energy detector consists of a square law device followed by a finite time integrator. The output of the integrator at any time is the energy of the input to the squaring device over the interval *T*. The noise pre-filter serves to limit the noise bandwidth; the noise at the input to the squaring device has a band-limited, flat spectral density.

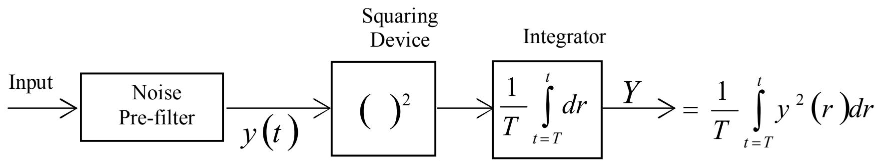

Fig. 1 Energy Detection

The local spectrum sensing is to decide between the following two hypotheses,

$$y(t) = \begin{cases} n(t) & H_0 \\ hs(t) + n(t) & H_1 \end{cases} \tag{1}$$

Where x(t) is the signal received by secondary user and s(t) is primary user's transmitted signal, n(t) is the additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. We also denote by γ the signal-to-noise ratio (SNR). The received signal is first pre-filtered by an ideal band-pass filter with transfer function [15] [16]

$$H(f) = \begin{cases} \dfrac{2}{\sqrt{N_{01}}}, & |f - f_c| \le W, \\ 0 & |f - f_c| > W, \end{cases} \tag{2}$$

to limit the average noise power and normalize the noise variance. The output of this filter is then squared and integrated over a time interval *T* to finally produce a measure of the energy of the received waveform. The output of the integrator denoted by *Y* will act as the test statistic to test the two hypotheses H_0 and H_1. According to the sampling theorem, the noise process [17] can be expressed as

$$n(t) = \sum_{i=-\infty}^{\infty} n_i \sin c(2Wt - i) \tag{3}$$

Where $\sin c(x) = \dfrac{\sin(\pi x)}{\pi x}$ and $n_i = n\left(\dfrac{i}{2W}\right)$

One can easily check that $n_i \approx N(0, N_{01}W)$, for all i. Using the fact that [17]

$$\int_{-\infty}^{\infty} \sin c(2Wt - i) \sin c(2Wt - k) dt = 1/2W, \; i = k \\ = 0, \quad i \ne k \tag{4}$$

We may write

$$\int_{-\infty}^{\infty} n^2(t)dt = \frac{1}{2W}\sum_{i=-\infty}^{\infty} n_i^{\,2} \tag{5}$$

Over the time interval $(0,T)$, $n(t)$ the noise energy can be approximated by a finite sum of 2*TW* terms as

$$n(t) = \sum_{i=1}^{2TW} n_i \sin c(2Wt - i), \quad 0 < t < T \tag{6}$$

Similarly, the energy in a sample of duration *T* is approximated by 2*TW* terms of the right-hand side:

$$\int_{0}^{T} n^2(t)dt = \frac{1}{2W}\sum_{i=1}^{2u} n_i^{\,2} \tag{7}$$

Where *u=TW* . We assume that *T* and *W* are chosen to restrict *u* to integer values. If we define

$$n_i^{'} = \frac{n_i}{\sqrt{N_{01}W}} \tag{8}$$

Where N_{01} =one-sided noise power spectral density. Then, the test or decision statistic *Y* can be written as

$$Y = \sum_{i=1}^{2u} n_i^{'2} \tag{9}$$

Y can be viewed as the sum of the squares of 2*u* standard Gaussian variates with zero mean and unit variance. Therefore, *Y* follows [15] a central chi-square (χ^2)distribution with *2u* degrees of freedom. The same approach is applied when the signal *s(t)* is present with the replacement of each n_i by $n_i + s_i$ where $s_i = s\left(\frac{i}{2W}\right)$. The decision statistic *Y* in this case will have a non-central χ^2 distribution with 2*u* degrees of freedom and a non-centrality parameter 2λ . Following the short-hand notations mentioned in the beginning of this section, we can describe the decision statistic as

$$Y \approx \begin{cases} \chi_{2u}^{\;2} & H_0 \\ \chi_{2u}^{\;2}(2\gamma)' & H_1 \end{cases} \tag{10}$$

The probability density function (PDF) [15] of *Y* can then be written as

$$f_Y(y) = \begin{cases} \dfrac{1}{2^u \Gamma(u)} y^{u-1} e^{-\frac{y}{2}} & H_0 \\ \dfrac{1}{2}\left(\dfrac{y}{2\gamma}\right)^{\frac{u-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{u-1}\left(\sqrt{2\gamma y}\right), & H_1 \end{cases} \tag{11}$$

Where $\Gamma(.)$ is the gamma function. The probability of detection and false alarm can be generally computed by [14-20]

$$P_d = \Pr(Y > \lambda \mid H_1) \tag{12}$$

$$P_f = \Pr(Y > \lambda \mid H_0) \tag{13}$$

Where λ is the final threshold of the local detector to decide whether there is a primary user present. Using (11) to evaluate (13) yields

$$P_f = \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma(u)}, \tag{14}$$

Hence,

$$P_d = Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \tag{15}$$

Where $\gamma = \frac{\sigma_x^{\ 2}}{2\sigma_n^{\ 2}} = \frac{\sigma_x^{\ 2}}{2}$ denotes the signal to noise ratio [21] (SNR), Q_u is the generalized Marcum's Q function.

3 DETECTION AND FALSE ALARM PROBABILITIES

In this section, we give the average detection probability over Rayleigh fading channel and in closed form [15]. In communications theory, Rayleigh distributions are used to model scattered signals that reach a receiver by multiple paths.

3.1 NON-FADING ENVIRONMENT (AWGN CHANNEL)

In non-fading environment the average probability of false alarm, the average probability of detection, and the average probability of missed detection are given, respectively, by [15]

$$P_d = P\{Y > \lambda \mid H_1\} = Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \tag{16}$$

$$P_f = P\{Y > \lambda \mid H_0\} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \tag{17}$$

and

$$P_m = 1 - P_d$$

(18)

where λ denotes the energy threshold. Γ(.) and Γ(.,.) are complete and incomplete gamma functions respectively [22] and $Q_u(.,.)$ is the generalized Marcum Q-function defined as follows,

$$Q_u(a,b) = \int_0^\infty \frac{x^u}{a^{u-1}} e^{-\frac{x^2+a^2}{2}} I_{u-1}(ax)dx \tag{19}$$

where $I_{u-1}(.)$ is the modified Bessel function of (u−1)th order. If the signal power is unknown, we can first set the false alarm probability P_f to a specific constant. By equation (17), the detection threshold λ can be determined. Then, for the fixed number of samples 2TW the detection probability P_d can be evaluated by substituting the λ in (16). As expected, P_f is independent of γ since under H_0 there is no primary signal present. When *h* is varying due to fading, equation (16) gives the probability of detection as a function of the instantaneous SNR, γ. In this case, the average probability of detection P_d may be derived by averaging (16) over fading statistics [10],

$$P_d = \int_x Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) f_\gamma(x) dx \tag{20}$$

Where *fγ(x)* is the probability distribution function (PDF) of SNR under fading.

3.2 RAYLEIGH FADING CHANNELS

When the composite received signal consists of a large number of plane waves, for some types of scattering environments, the received signal has a Rayleigh distribution [23]. If the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by

$$f(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right), \ \gamma \geq 0 \tag{21}$$

In this case, a closed-form formula for P_d may be obtained (after some manipulation) by substituting $f_\gamma(x)$ in (19),

$$\overline{P}_{dRay} = e^{-\frac{\lambda}{2}} \sum_{k=0}^{u-2} \frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{u-1} \times \left(e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}\sum_{k=0}^{u-2}\frac{1}{k!}\left(\frac{\lambda\bar{\lambda}}{2(1+\bar{\gamma})}\right)} \right) \tag{22}$$

4 COOPERATIVE SPECTRUM SENSING OVER VARIOUS FADING CHANNELS

Let *N* denote the number of users sensing the PU. Each CR user makes its own decision regarding whether the primary user present or not, and forwards the binary decision (1 or 0) to fusion center (FC) for data fusion. The PU is located far away from all CRs. All the CR users receive the primary signal with same local mean signal power, i.e. all CRs form a cluster with distance between any two CRs negligible compared to the distance from the PU to a CR. For simplicity we have assumed that the noise, fading statistics and average SNR are the same for each CR user. We consider that the channels between CRs and FC are ideal channels (noiseless). Assuming independent decisions, the fusion problem where *k* out of *N* CR users are needed for decision can be described by binomial distribution based on Bernoulli trials where each trial represents the decision process of each CR user. With a hard decision counting rule, the fusion center implements an *n*–out-of-*M* rule that decides on the signal present hypothesis whenever at least *k* out of the *N* CR user decisions indicate H_1. Assuming uncorrelated decisions, the probability of detection at the fusion center [24] is given by

$$P_d = \sum_{l=k}^{N} \binom{N}{l} P_{d,i}{}^{l} \left(1 - P_{d,i}\right)^{N-l} \tag{23}$$

$$P_f = \sum_{l=k}^{N} \binom{N}{l} P_{f,i}{}^{l} \left(1 - P_{f,i}\right)^{N-l} \tag{24}$$

Where $P_{d,i}$ is the probability of detection for each individual CR user as defined by (3) and (6).

AND-Rule:- In this rule, if all of the local decisions sent to the decision maker are one, the final decision made by the decision maker is one. Cooperative detection performance with this fusion rule can be evaluated by setting *k*=*N* in eq. (23).

The cooperative probability of detection using AND rule is

$$P_{d,AND} = \Pr\{Fusiondecision = 1 \mid H_1\} = \prod_{i=1}^{N} Pd_i \tag{25}$$

The cooperative probability of false alarm using AND rule is

$$P_{f,AND} = \Pr\{Fusiondecision = 1 \mid H_0\} = \prod_{i=1}^{N} Pf_i \tag{26}$$

The cooperative probability of misdetection using hard decision AND rule is

$$P_{Pm,AND} = 1 - \left(P_{d,AND}\right)$$

$$= 1 - \left(\prod_{i=1}^{N} Pd_i \right) \quad (27)$$

OR-Rule:- In this rule, if any one of the local decisions sent to the decision maker is a logical one, the final decision made by the decision maker is one. Cooperative detection performance with this fusion rule can be evaluated by setting *k*=1 in eq. (23).

The cooperative probability of detection using OR rule is

$$P_{d,OR} = \Pr\{Fusiondecision = 1 \mid H_1\} = 1 - \prod_{i=1}^{N} (1 - Pd_i) \quad (28)$$

The cooperative probability of false alarm using OR rule is

$$P_{f,OR} = \Pr\{Fusiondecision = 1 \mid H_0\} = 1 - \prod_{i=1}^{N} (1 - Pf_i) \quad (29)$$

The cooperative probability of misdetection using OR rule is

$$P_{Pm,OR} = 1 - (P_{d,OR}) \quad (30)$$

This can also be written as

$$P_{Pm,OR} = 1 - \left(1 - \prod_{i=1}^{N} (1 - Pd_i) \right) \quad (31)$$

$$= \prod_{i=1}^{N} (1 - Pd_i) \quad (32)$$

MAJORITY-Rule:- In this rule, if half or more of the local decisions sent to the decision maker are the final decision made by the decision maker is one. Cooperative detection performance with this fusion rule can be evaluated by setting $k = \lfloor N/2 \rfloor$ in eq. (23).

$$P_{d,MAJ} = \sum_{l=\lfloor N/2 \rfloor}^{N} \binom{N}{l} P_{d,i}{}^{l} (1 - P_{d,i})^{N-l} \quad (33)$$

Where $\lfloor . \rfloor$ represents the floor operator.

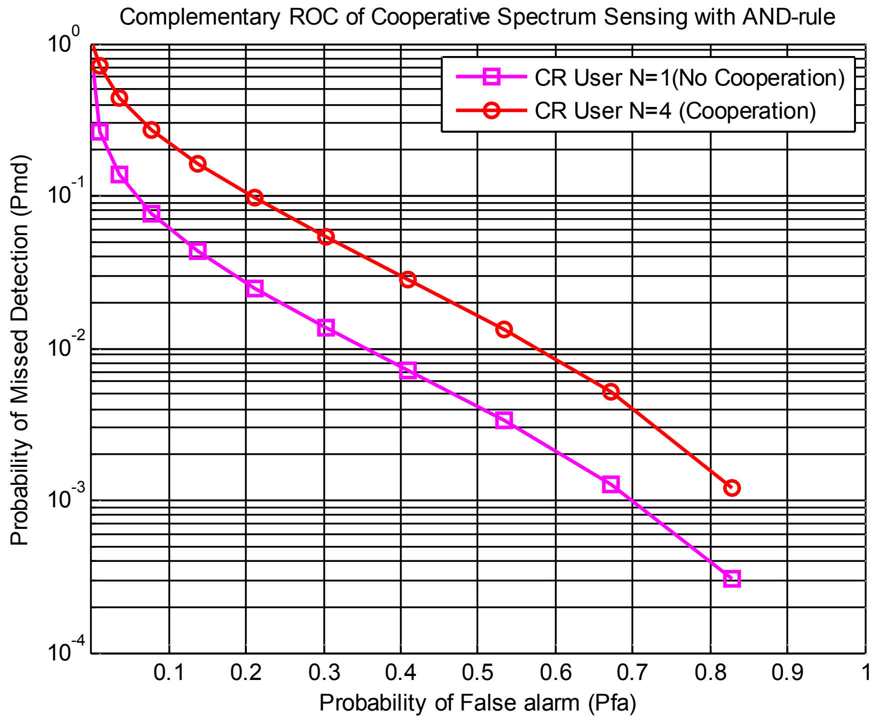

Fig.2 Complementary ROC of AND fusion rule over Rayleigh fading channel ($\bar{\gamma}$=10dB, u=5)

5 Simulation Result and Discussion

All simulation was done on MATLAB version R2011a over Rayleigh fading channel and a non-fading AWGN channel.

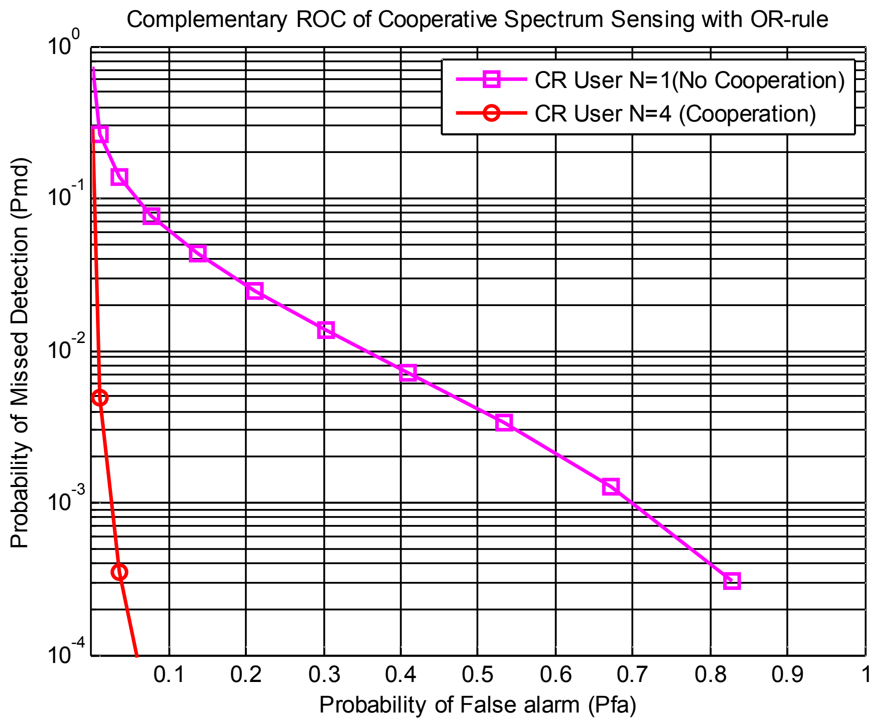

Fig.3 Complementary ROC of OR fusion rule over Rayleigh fading channel ($\bar{\gamma}$=10dB, u=5)

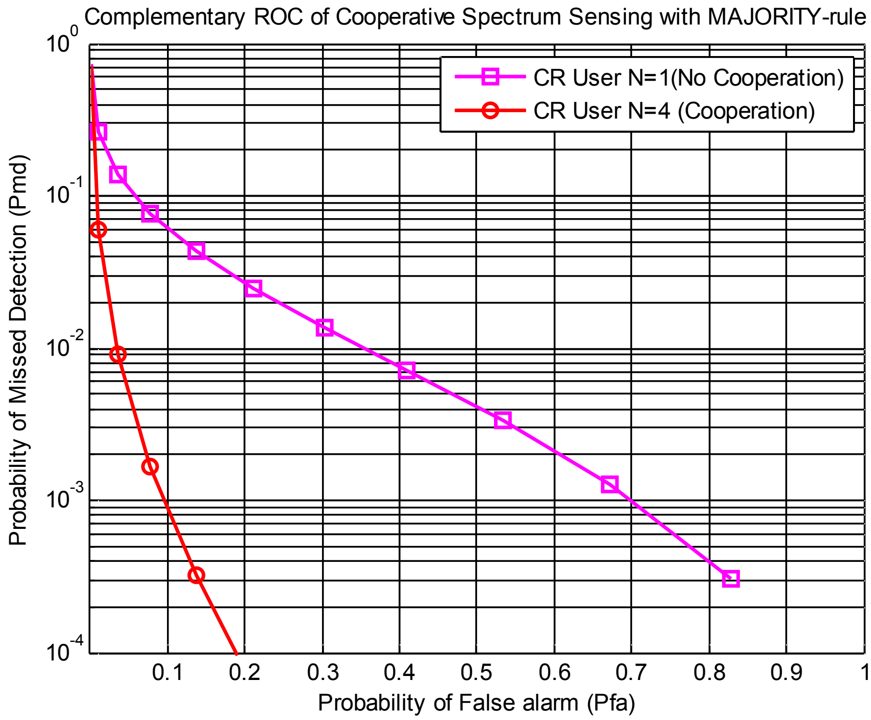

Fig.4 Complementary ROC of MAJORITY fusion rule over Rayleigh fading channel ($\bar{\gamma}$=10dB, u=5)

Fig 2, 3 and 4 show complementary ROC curves of cooperative spectrum sensing in Rayleigh fading following AND rule, OR rule and MAJORITY rule respectively. Average SNR and *u* are assumed to be 10 dB and 5 respectively. A plot for non-cooperative spectrum sensing case is also provided for comparison. Fig. 2 shows, probability of missed detection is decreasing according to the increasing probability of false alarm. Fig. 3 shows, probability of missed detection is decreasing more than fig.2 according to the increasing probability of false alarm. And fig. 4 shows, probability of missed detection is decreasing more than fig.2 and less than fig.3 according to the increasing probability of false alarm. In fig 2, 3 and 4 also shows that spectrum sensing is better in presence of cooperative than non-cooperation over Rayleigh fading channel.

6 CONCLUSION

We have discussed cooperative spectrum sensing based on energy detection in CR networks. Cooperative spectrum sensing improves the detection performance. We also have studied cooperative spectrum sensing over Rayleigh fading channel. The performance of ED-CSS also has been investigated via probability of missed detection versus different probability of false alarm values in Rayleigh fading channel. Performance of cooperative spectrum sensing over Rayleigh fading is presented and compared with the non-cooperative spectrum sensing. In this paper, the sensing of primary user in a cooperative spectrum sensing model under Rayleigh fading was investigated by implementing the local spectrum sensing with the energy detection technique. We observe that the OR rule has the better performance than AND and MAJORITY rule. We also observe that spectrum sensing is better in presence of cooperation.

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