International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 1 No. 1 Nov. 2012, pp. 84-93

http://www.issr-journals.org/ijias/

Cooperative Spectrum Sensing over Fading Channel in Cognitive Radio

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ABSTRACT: Spectrum sensing is the key component of cognitive radio technology. Spectrum sensing is a tough task because of shadowing, fading, and time-varying nature of wireless channels. 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 focus performance of cooperative spectrum sensing over Rayleigh and Nakagami fading channel with comparable non-fading AWGN channel in cognitive radio. This paper presents a simulation comparison of these fading channels based on fusion rule OR-rule, AND-rule and MAJORITY-rule. We observe that spectrum sensing is harder in presence of Rayleigh and Nakagami fading and performance of energy detection degrades more in Nakagami channels than Rayleigh channel and non-fading AWGN channel.

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

1 INTRODUCTION

Cognitive radio (CR) technique has been proposed to solve the conflicts between spectrum scarcity and spectrum under-utilization [1]. It allows the CR users to share the spectrum with primary users (PU) by opportunistic accessing. The CR can use the spectrum only when it does not cause interference to the primary users. Therefore, spectrum sensing is a critical issue of cognitive radio technology since it needs to detect the presence of primary users accurately and swiftly. Existing spectrum sensing techniques can be divided into three types [2]: energy detection, matched filter detection and cyclostationary detection. Among them, energy detection has been widely applied since it does not require any a priori knowledge of primary signals and has much lower complexity than the other two schemes. The radio channel is characterized by two types of fading effects: large scale fading and small scale fading [3], [4]. Small scale fading models include the well-known Rayleigh, Rice, and Nakagami-m [5]-[6] distributions. For large scale fading conditions, it is widely accepted that the probability density function (PDF) of the fading envelopes can be modeled by the well-known Log-normal distribution [7], [8]. Due to the several multipath fading, a cognitive radio may fail to notice the presence of the PU and then will access the licensed channel and cause interference to the PU. To combat these impacts, cooperative spectrum sensing schemes have been proposed to obtain the spatial diversity in multiuser CR networks [9-11]. The performance of cooperative spectrum sensing in Cognitive Radio over fading channel has been evaluated in [13-16]. However, the existed works only examined the additive white Gaussian noise (AWGN) channel and the Rayleigh fading channel. In this paper, we study cooperative spectrum sensing over Rayleigh and Nakagami fading channel and comparable with non-fading AWGN channel in cognitive radio.

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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 fading channel such as Rayleigh and Nakagami are described. Cooperative spectrum sensing in fading channels is derived in Section IV. The simulation result and discussion are presented in section V. Finally, we draw our conclusions in Section VI.

2 SYSTEM MODEL

We assume that energy detection [17] 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.

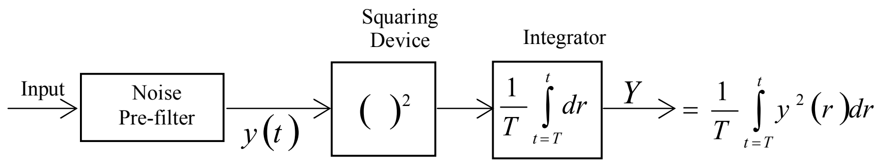

Fig. 1. Energy Detection

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 [18] [19]:

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

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 [20] 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 [20]:

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

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 $2u$ standard Gaussian variates with zero mean and unit variance. Therefore, Y follows [18] 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 $2u$ 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) [18] 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.

3 DETECTION AND FALSE ALARM PROBABILITIES

In this section, we give the average detection probability over Rayleigh and Nakagami fading channels and in closed form:

A. 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 [18]:

$$P_d = P\{Y > \lambda \mid H_1\} = Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \tag{12}$$

$$P_f = P\{Y > \lambda \mid H_0\} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \tag{13}$$

and:

$$P_m = 1 - P_d \tag{14}$$

where λ denotes the energy threshold. $\Gamma(.)$ and $\Gamma(.,.)$ are complete and incomplete gamma functions respectively [25] and $Q_u(.,.)$ is the generalized Marcum Q-function defined as follows,

$$Q_u(a,b) = \int_0^{\infty} \frac{x^u}{a^{u-1}} e^{-\frac{x^2+a^2}{2}} I_{u-1}(ax)dx \tag{15}$$

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 (13), 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 (12). 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 (12) 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 (12) over fading statistics [21],

$$P_d = \int_x Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) f_\gamma(x)dx \tag{16}$$

where $f\gamma(x)$ is the probability distribution function (PDF) of SNR under fading.

B. 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 [22]. If the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by:

$$f(\gamma) = \frac{1}{\overline{\gamma}} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right), \ \gamma \geq 0 \tag{17}$$

In this case, a closed-form formula for P_d may be obtained (after some manipulation) by substituting $f_\gamma(x)$ in (16),

$$\overline{P}_{dRay} = e^{-\frac{\lambda}{2}} \sum_{k=0}^{u-2} \frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1} \times \left(e^{-\frac{\lambda}{2(1+\overline{\gamma})}} - e^{-\frac{\lambda}{2}\sum_{k=0}^{u-2}\frac{1}{k!}\left(\frac{\lambda\overline{\lambda}}{2(1+\overline{\gamma})}\right)} \right) \tag{18}$$

C. Nakagami fading channel

The Nakagami distribution was introduced by Nakagami in the early 1940's to characterize rapid fading in long distance HF channels [23]. The Nakagami m-distribution is used in communication systems characterize the statistics of signal transmitted through multipath fading channels. The Nakagami distribution is often used for the following reasons. First, the Nakagami distribution can model fading conditions that are either more or less severe than Rayleigh fading. When m=1, the Nakagami distribution becomes the Rayleigh distribution, when m=1/2, it becomes a one-sided Gaussian distribution, and when m=∞ the distribution becomes an impulse (no fading). Second, the Rice distribution can be closely approximated by using the following relation between the Rice factor K and the Nakagami shape factor m [23]:

$$K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}} \qquad m > 1$$

$$m = \frac{(K+1)^2}{(2K+1)}$$

Since the Rice distribution contains a Bessel function while the Nakagami distribution does not, the Nakagami distribution often leads to convenient closed form analytical expressions that are otherwise unattainable. Using the alternative representation of Marcum-Q function given in [24, eq. (4.74), pp. 104], (1) can be written as:

$$Q_u\left(\sqrt{2\gamma},\sqrt{\lambda}\right)=\sum_{n=0}^{\infty}\frac{\gamma^n e^{-\gamma}}{n!}\sum_{k=0}^{n+u-1}\frac{e^{-\frac{\lambda}{2}}}{k!}\left(\frac{\lambda}{2}\right)^k \tag{19}$$

If the signal amplitude follows a Nakagami distribution, then the PDF of γ follows a gamma PDF given by:

$$f(\gamma)=\frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}}\right)^m \gamma^{m-1}\exp\left(-\frac{m\gamma}{\bar{\gamma}}\right),\ \gamma\geq 0 \tag{20}$$

where m is the Nakagami parameter. The average P_d in the case of Nakagami channels $\overline{P}_{dNak}$ can now be obtained by averaging (12) over (20) and then using again the change of variable $x=\sqrt{2\gamma}$ yielding:

$$\overline{P}_{dNak}=\alpha\int_0^{\infty}x^{2m-1}\exp\left(-\frac{mx^2}{2\bar{\gamma}}\right)Q_u\left(x,\sqrt{\lambda}\right)dx \tag{21}$$

where:

$$\alpha=\frac{1}{\Gamma(m)2^{m-1}}\left(\frac{m}{\bar{\gamma}}\right)^m \tag{22}$$

In this case, a closed-form formula of Nakagami channels can be given by:

$$\overline{P}_{dNak}=\alpha\left[G_1+\beta\sum_{n=1}^{u-1}\frac{(\lambda/2)}{2(n!)}\,{}_1F\left(m;n+1;\frac{\lambda}{2}\frac{\bar{\gamma}}{m+\bar{\gamma}}\right)_1\right] \tag{23}$$

where ${}_1F_1(.;.;.)$ is the confluent hyper geometric function [25].

$$\beta=\Gamma(m)\left(\frac{2\bar{\gamma}}{m+\bar{\gamma}}\right)^m e^{-\lambda/2} \tag{24}$$

and:

$$G_1=\int_0^{\infty}x^{2m-1}\exp\left(-\frac{mx^2}{2\bar{\gamma}}\right)Q_u\left(x,\sqrt{\lambda}\right)dx \tag{25}$$

Where Q(.,.)=Q(.,.) is the first-order Marcum Q-function. G1 can be evaluated for inter m with the aid of [25, Eq.(25)]

$$G_1=\frac{2^{m-1}(m-1)!}{\left(\frac{m}{\bar{\gamma}}\right)^m}\frac{\bar{\gamma}}{m+\bar{\gamma}}e^{-\frac{\lambda}{2}\frac{m}{m+\bar{\gamma}}}\left|\left(1+\frac{m}{\bar{\gamma}}\right)\left(\frac{m}{m+\bar{\gamma}}\right)^{m-1}\times L_{m-1}\left(-\frac{\lambda}{2}\frac{\bar{\gamma}}{m+\bar{\gamma}}\right)+\sum_{n=0}^{m-2}\left(\frac{m}{m+\bar{\gamma}}\right)^n L_n\left(-\frac{\lambda}{2}\frac{\bar{\gamma}}{m+\bar{\gamma}}\right)\right| \tag{26}$$

where is the Laguerre polynomial of degree n [26, 8.970].

4 COOPERATIVE SPECTRUM SENSING IN 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 [27] is given by:

$$P_d = \sum_{l=k}^{N} \binom{N}{l} P_{d,i}{}^{l} \left(1 - P_{d,i}\right)^{N-l} \tag{27}$$

where $P_{d,i}$ is the probability of detection for each individual CR user as defined by (12) and (16).

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. The fusion center's decision is calculated by logic AND of the received hard decision statistics. Cooperative detection performance with this fusion rule can be evaluated by setting $k=N$ in eq. (27):

$$P_{d,AND} = P_{d,i}{}^{N} \tag{28}$$

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. (27):

$$P_{d,OR} = 1 - \left(1 - P_{d,i}\right)^{N} \tag{29}$$

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. (27):

$$P_{d,MAJ} = \sum_{l=\lfloor N/2 \rfloor}^{N} \binom{N}{l} P_{d,i}{}^{l} \left(1 - P_{d,i}\right)^{N-l} \tag{30}$$

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

5 SIMULATION RESULT AND DISCUSSION

All simulation was done on MATLAB version R2011a over two different fading under Rayleigh and Nakagami channel and a non-fading channel AWGN. We described the receiver through its complementary ROC curves for different values of probability of false alarm and Cognitive Radio user.

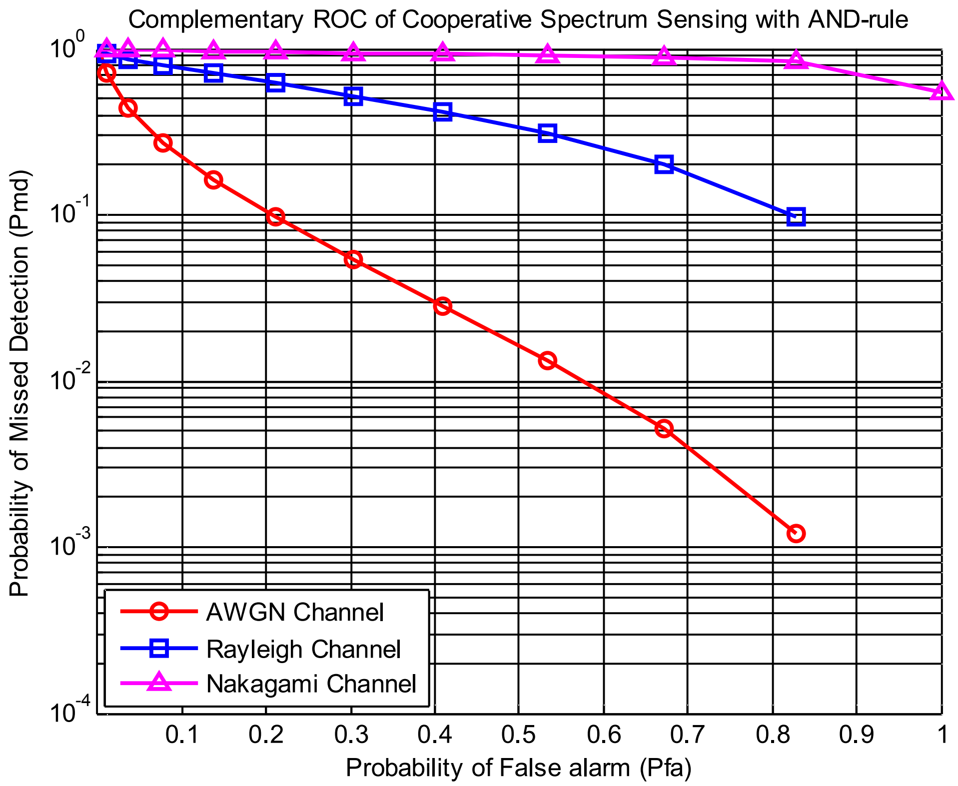

Fig. 2. Complementary ROC of AND fusion rule over fading channel ($\bar{\gamma}$=10dB, N=4, u=5 and m=3)

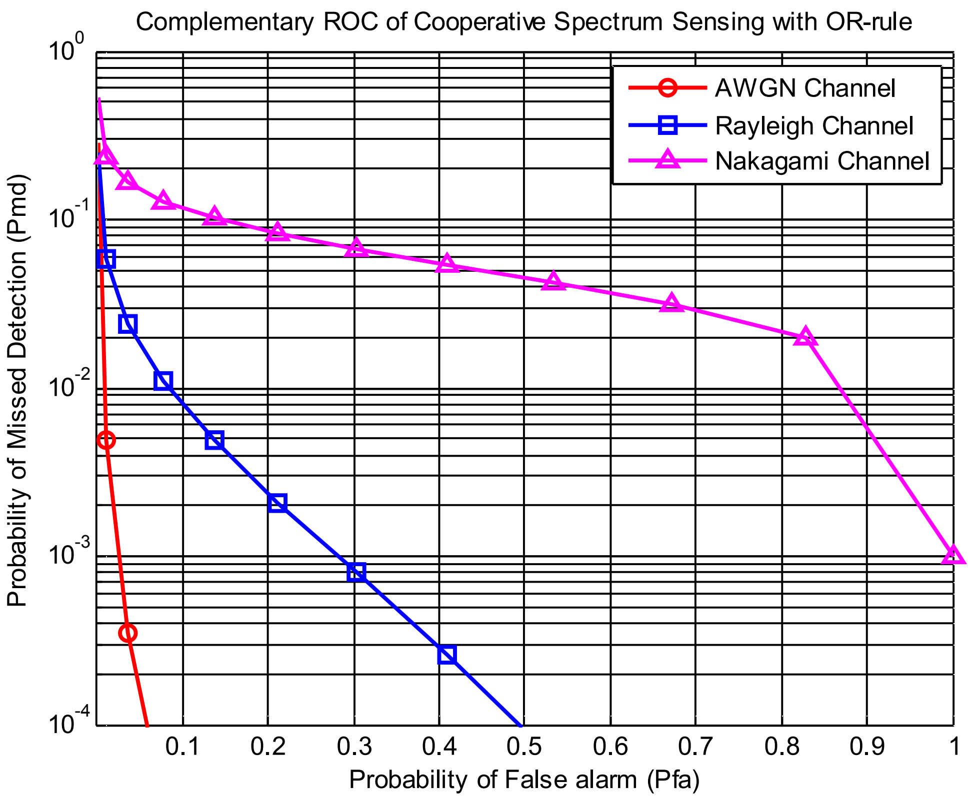

Fig. 3. Complementary ROC of OR fusion rule over fading channel ($\bar{\gamma}$=10dB, N=4, u=5 and m=3)

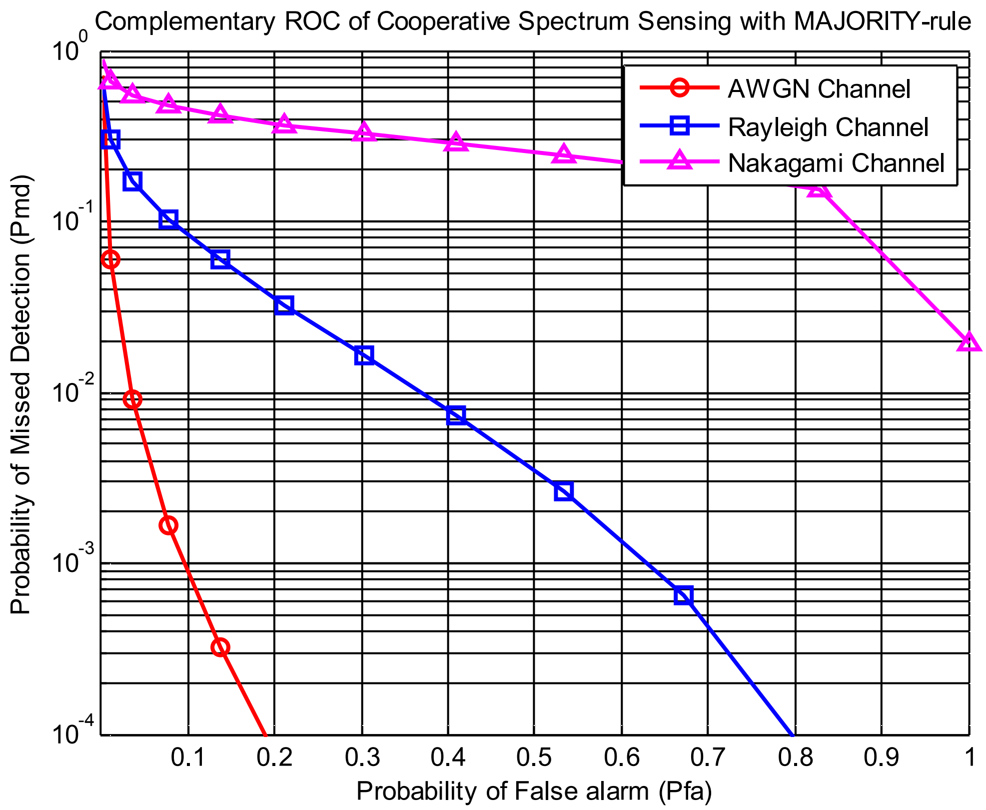

Fig. 4. Complementary ROC of MAJORITY fusion rule over fading channel ($\bar{\gamma}$=10dB, N=4, u=5 and m=3)

Fig. 2, 3 and 4 show complementary ROC curves of the 4 user's spectrum sensing in two different fading under Rayleigh and Nakagami fading following AND rule, OR rule and MAJORITY rule respectively. A plot for non-fading (pure AWGN) case is also provided for comparison. Average SNR and u are assumed to be 10 dB and 5 respectively. Nakagami parameter m is set to be 3. In fig.2, 3 and 4 are shown that probability of missed detection is decreased based on increasing the probability of false alarm. Spectrum sensing is verified in this simulation by taking different number of false alarm. Spectrum sensing in non-fading AWGN channel is better than fading channel. Comparing the AWGN curve with those corresponding to fading, we observe that spectrum sensing is harder in presence of Rayleigh and Nakagami fading. We also observe that the OR rule has the better performance than AND and MAJORITY rules in various channels.

6 CONCLUSION

We have studied cooperative spectrum sensing over Rayleigh and Nakagami fading channel in cognitive radio with non-fading AWGN channel. Performance of cooperative spectrum sensing over Rayleigh and Nakagami fading are presented and compared with the non-fading AWGN channel. It has been found that probability of missed detection is decreased by using different fusion rules. We observe that the OR rule has the better performance than AND and MAJORITY rule in various channels. We also observe that spectrum sensing is harder in presence of Rayleigh and Nakagami fading and performance of energy detection degrades more in Nakagami channels than Rayleigh channels.

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