Energy detection based techniques for Spectrum sensing in Cognitive Radio over different fading Channels

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***Abstract*—Energy detection is the most popular spectrum sensing method in cognitive radio. This paper focuses on energy detection based spectrum sensing because of its low complexity. As it does not require proper knowledge of channel gains, and estimations of other parameters it is also considered as a low cost option. Different other spectrum sensing methods like matched filter detection, cyclostationary feature detection etc. need to know the prior information i.e. frequency, phase, modulation scheme etc. about the primary signal whereas energy detection does not and it is also simpler to implement. In this paper, we compare the ROC (Receiver Operating Characteristics), complementary ROC curves and probability of detection (P_d) versus SNR (Signal-to-Noise Ratio) curves for AWGN, log-normal, Hoyt (or Nakagami-*q*), Rayleigh, Rician (or Nakagami-*n*), Nakagami-*m*, and Weibull channels with and without considering diversity techniques. Both the results are compared and it showed that energy detection based spectrum sensing technique over various fading channel considering diversity case has better performance than for no diversity case.**

***Index Terms*—Cognitive Radio(CR), Spectrum Sensing, Energy Detection, Detection Probability.**

I. INTRODUCTION

With rising demand and usage of radio spectrum, the efficient use of available licensed spectrum is becoming more and more decisive. To satisfy the dramatic increasing demand for radio spectrum, cognitive radio *(CR)* is proposed as a key technology to realize the dynamic spectrum allocation. To use spectrum efficiently and intelligently as targeted in cognitive radio and dynamic spectrum access, spectrum sensing is essential. Among existing spectrum sensing techniques, energy detection [1] is mostly used. This is because as a non coherent detection technique energy detection does not require any prior information about the transmitted signal. As a result, energy detection is not only simple in implementation but also robust in various operating environments. The performance of energy detection in fading channels has been extensively studied in [2]–[5].

In energy detection method, we measure the energy of the received signal and compare it with a predefined threshold to determine the presence or absence of primary user's signal. Moreover, energy detector is mainly used in ultra wideband communication to borrow an idle channel from licensed user. In this paper, probability of detection (P_d) probability of false alarm (P_f) and probability of missed detection ($P_m = 1 - P_d$) are the key measurement metrics that analyze the performance of an energy detector. The performance of an energy detector is illustrated by probability of detection (P_d) versus SNR curves and the complementary receiving operating characteristics (CROC) curves which is a plot of (P_d)versus (P_f) or (P_m) versus(P_f).

The rest of the paper is organized as follows. In Section II, energy detection and channel model is described and we briefly describe the probabilities of detection and of false alarm over additive white Gaussian noise (AWGN) channel, shadowing and fading channels. Our simulation results and discussions are presented in Section III. Finally we conclude in Section IV.

II. Energy Detection and Channel MODEL

Energy detection is a non coherent detection method that is used to detect the licensed User signal. [6]. It is a simple method in which prior knowledge of primary or licensed user signal is not required, it is one of popular and easiest sensing technique of non-cooperative sensing in cognitive radio networks [7]-[8]. If the noise power is known, then energy

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detector is good choice [9]. Mathematical model for Energy detection is given by the following two hypotheses H_0 and H_1 :

H_0: (primary user absent)
y(n) = u(n) n = 1, 2, . . . ,N
H_1: (primary user present)
y(n) = s(n) + u(n) n = 1, 2, . . . ,N (1)
Where u (n) is noise and s (n) is the primary user signal.

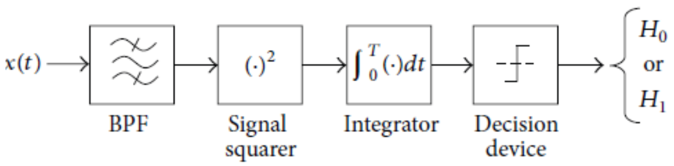

Figure 1: Block diagram of an energy detector

Figure 1 shows the block diagram of an energy detector. The band pass filter selects the specific band of frequency to which user wants to sense. After the band pass filter there is a squaring device which is used to measure the received energy. The energy which is found by squaring device is then passed through integrator which determines the observation interval T. Now the output of integrator is compared with a value called threshold and if the values are above the threshold, it will consider that primary user is present otherwise absent.

A. Energy detection and False alarm Probabilities

The probability of detection and probability of false alarm in nonfaded, that is, AWGN channel and faded environments are studied in this section.

A1. Over AWGN Channel

In energy detection, the received signal is first pre-filtered by an ideal bandpass filter which has bandwidth W, and the output of this filter is then squared and integrated over a time interval T to produce the test statistic. The test statistic Y is compared with a predefined threshold value λ [10]. The probabilities of false alarm (P_f) and detection (P_d) can be evaluated as $P_r(Y > \lambda|H_0)$ a nd $P_r(Y > \lambda|H_1)$ respectively to yield [11]

$$P_f = \frac{\Gamma\left(\mu, \frac{\lambda}{2}\right)}{\Gamma(\mu)} \quad (2)$$

$$P_d = Q_\mu\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \quad (3)$$

where $u = WT$, γ is SNR given as $E_s|h|^2/N_0$, E_s is the is the power budget at the primary user, $Q_\mu(.\,,.)$ is the uth order generalized Marcum-Q function, $\Gamma(.)$ is the gamma function, and $\Gamma(.,.)$ is the upper incomplete gamma function. Probability of false alarm P_f can easily be calculated using (3), because it does not depend on the statistics of the wireless channel. In the sequel, detection probability is focused. The generalized Marcum-Q function can be written as a circular contour integral within the contour radius $r \in [0, 1)$. Therefore, expression (4) can be re-written as [12]

$$P_d = \frac{e^{\frac{-\lambda}{2}}}{j2\pi} \oint_\Omega \frac{e^{\left(\frac{1}{z}-1\right)\gamma + \frac{\lambda}{2}z}}{z^u(1-z)} dz \quad (4)$$

where Ω is a circular contour of radius $r \in [0, 1)$. The moment generating function (MGF) of received SNR γ is $M_\gamma(s) = E(e^{-s\gamma})$,where E(.) means expectation. Thus, the average detection probability $\overline{P_d}$,is given by

$$\overline{P_d} = \frac{e^{\frac{-\lambda}{2}}}{j2\pi} \oint_\Omega g(z)dz \quad (5)$$

Where

$$g(z) = M_\gamma\left(1 - \frac{1}{z}\right) \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)}$$

Since the Residue Theorem [13] in complex analysis is a powerful tool to evaluate line integrals and/or real integrals of functions over closed curves, it is applied for the integral in(5).

A2. Fading Environment

In this case, the average probability of detection $\overline{P_d}$ may be derived by averaging (3) over fading statistics [14],

$$\bar{P}_d = \int_0^\infty Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) f_\gamma(\gamma)\, d\gamma \quad (6)$$

where, $f_\gamma(\gamma)$ is the PDF of SNR under fading.The expression for P_f given in (2) remains the same for fading case due to independency of γ. In the following subsequent sections, various statistical models of several fading channels such as log-normal shadowing, Hoyt

(Nakagami-q), Rayleigh, Rician, Nakagami-m, andWeibull fading channels are studied.

B. Log-Normal Shadowing Channel.

The linear channel gain may be modeled by Log-normal random variable e^X, where X is a zero-mean Gaussian random variable with variance σ^2 Log-normal shadowing is usually characterized in terms of its dB-spread, σ_{dB}
which is related to σ by $\sigma = 0.1 \ln(10)\ \sigma_{dB}$ [14]

C. Hoyt or Nakagami-q Fading Channel

Hoyt or Nakagami-q distribution is generally used to characterize the fading environments that are more severe than Rayleigh fading. The PDF of γ, that is $f_\gamma(\gamma)$, may be defined as [15,16].

$$f_\gamma = \frac{1}{\sqrt{p}} exp\left(-\frac{\gamma}{p\bar{\gamma}}\right) I_o\left(\frac{\gamma\sqrt{1-p}}{p\bar{\gamma}}\right); \gamma \geq 0 \tag{7}$$

Where

$$p = \frac{4q^2}{(1+q^2)^2}; \quad 0 \leq p \leq 1 \tag{8}$$

where q is the fading severity parameter. The average P_d in this case, $\overline{P}_{d,Hoyt}$ can now be evaluated by substituting $f_\gamma(\gamma)$ from (7) to (6).

D. Rayleigh Fading Channel

If the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by [17]

$$f_\gamma(\gamma) = \frac{1}{\gamma} exp\left(-\frac{\gamma}{\bar{\gamma}}\right); \gamma \geq 0 \tag{9}$$

The average P_d in this case, $\overline{P}_{d,Ray}$ can be evaluated by substituting (9) in (6):

$$\begin{aligned}\overline{P}_{d,Ray} = {} & \exp\left(-\frac{\lambda}{2}\right)\sum_{k=0}^{u-2}\frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\overline{\gamma}}{\overline{\gamma}}\right)^{u-1} \\ & \times \left(\exp\left(-\frac{\lambda}{2(1+\overline{\gamma})}\right) - \exp\left(-\frac{\lambda}{2}\right)\right. \\ & \left.\times \sum_{k=0}^{u-2}\frac{1}{k!}\left(-\frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right)^k\right)\end{aligned} \tag{10}$$

E. Rician Fading Channel

If the If the signal strength follows a Rician distribution, the PDF of γ will be [18]

$$f_\gamma(\gamma) = \frac{K+1}{\bar{\gamma}} exp\left(-K - \frac{(K+1)\gamma}{\bar{\gamma}}\right) I_o \times \left(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}}}\right), \ \gamma \geq 0 \tag{11}$$

where K is the Rician factor. The average P_d in the case of a Rician channel, $\overline{P}_{d,Ric}$ is then obtained by substituting (11) in (6). The resulting expression can be solved for $u = 1$ to yield

$$\overline{P}_{d,Ric|u=1} = Q\left(\sqrt{\frac{2K\bar{\gamma}}{K+1+\bar{\gamma}}}, \sqrt{\frac{\lambda(K+1)}{K+1+\bar{\gamma}}}\right) \tag{12}$$

For $K = 0$, this expression reduces to the Rayleigh expression with $u = 1$ [18].

F. Nakagami-m fading Channel

If the signal amplitude follows a Nakagami-m distribution, then PDF of γ follows a gamma PDF given by [17]

$$f_\gamma(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} exp\left(-\frac{m\gamma}{\bar{\gamma}}\right); \gamma \geq 0 \tag{13}$$

where m is the Nakagami parameter. The average P_d in the case of Nakagami-m fading channel $\overline{P}_{d,Nak}$ can be evaluated by substituting (13) in (6):

$$\overline{P}_{d,Nak} = \alpha\left[G_1 + \beta\sum_{n=1}^{u-1}\frac{\left(\frac{\lambda}{2}\right)^n}{2n!} {}_1F_1\left(m; n+1; \frac{\lambda\bar{\gamma}}{2(m+\bar{\gamma})}\right)\right] \tag{14}$$

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

$$\beta = \Gamma(m)\left(\frac{2\bar{\gamma}}{m+\bar{\gamma}}\right)^m \exp\left(-\frac{\lambda}{2}\right) \tag{15}$$

$$G_1 = \frac{2^{m-1}(m-1)!\,\overline{\gamma}}{(m/\overline{\gamma})^m(m+\overline{\gamma})} \exp\left(-\frac{m\lambda}{2(m+\overline{\gamma})}\right) \times$$

$$\left[\left(1+\frac{m}{\bar{\gamma}}\right)\left(\frac{m}{m+\bar{\gamma}}\right)^{m-1} L_{m-1}\left(-\frac{\lambda\bar{\gamma}}{2(m+\bar{\gamma})}\right)+\sum_{n=0}^{m-2}\left(\frac{m}{m+\bar{\gamma}}\right)^{n} L_{n}\left(-\frac{\lambda\bar{\gamma}}{2(m+\bar{\gamma})}\right)\right] \quad (16)$$

where $L_n(.)$ is the Laguerre polynomial of degree n. We can obtain an alternative expression for $\overline{P}_{d,Ray}$ when setting m=1 in (16) and this expression is numerically equivalent to the one obtained in (10)

G. Weibull Fading Channel

In theWeibull fading model, the channel fading coefficient h can be expressed as a function of the Gaussian in-phase X and quadrature Y elements of the multipath components [19, 20]

$$h = (X + jY)^{2/V} \quad (17)$$

Where $j = \sqrt{-1}$

Let Z be the magnitude of h, that is, $Z = |h|$. If $R = |X + jY|$ is a Rayleigh distributed random variable, the Weibull
distributed random variable can be obtained by transforming R and using (17) as

$$Z = R^{2/V} \quad (18)$$

From (18), the PDF of Z can be given as

$$f_Z(r) = \frac{V}{S} r^{V-1} \exp\left(-\frac{r^V}{S}\right) \quad (19)$$

with $S = E(Z^V)$ and $E(.)$ denoting the expectation. V is the Weibull fading parameter expressing how severe the fading can be ($V > 0$) and S is the average fading power. As V increases, the effect of fading decreases, while for the special case of $V = 2$, the Weibull PDF of Z reduces to the Rayleigh PDF. For $V = 1$ the Weibull PDF of Z reduces to the well known negative exponential PDF

The corresponding CDF of Z can be expressed as [21]

$$F_Z(r) = 1 - \exp\left(-\frac{r^V}{S}\right) \quad (20)$$

In Weibull fading the instantaneous signal-to-noise ratio at a cognitive radio is given by [22]

$$\gamma = Z^2 \frac{E_S}{N_{01}} \quad (21)$$

It may be noted that the nth power of a Weibull distributed random variable with parameters (V, S) is another Weibull distributed random variable with parameters (V/n, S) [23].Thus γ is also a Weibull distributed random variable with parameters $(V/2, (a\bar{\gamma})^{\frac{V}{2}})$ where $a = 1/\Gamma(1 + 2/V)$. The PDF of γ can then be derived from (13) by replacing V with $V/2$ and S with $(a\bar{\gamma})^{\frac{V}{2}}$ as [24]

$$f_\gamma(\gamma) = \frac{V}{2(a\bar{\gamma})^{V/2}} (\gamma)^{(V/2-1)} \exp\left[-\left(\frac{\gamma}{a\bar{\gamma}}\right)^{V/2}\right] \quad (22)$$

Where $\bar{\gamma}$ is the average SNR given as

$$\bar{\gamma} = E(Z^2)\frac{E_S}{N_{01}} = S^{2/V}\Gamma\left(1+\frac{2}{V}\right)\frac{E_S}{N_{01}} \quad (23)$$

Here, $E(Z)^2$ the second moment of Zwhich can be obtained from the generalized expression for moments as [22]

$$E(Z^n) = S^{n/V}\Gamma\left(1+\frac{n}{V}\right) \quad (24)$$

where n is a positive integer and $\Gamma(.)$ is the Gamma function.The average P_d in the case of a Weibull channel
$\overline{P}_{d,\ Weibu}$ can be obtained analytically by substituting (22) in (6).

In above discussed sections, we address the energy detection performance with no diversity schemes. Now, let us consider the energy detection performance with few diversity techniques like MRC and SC.

i. Maximal Ratio Combining (MRC):

The MRC is a coherent combining technique which needs CSI in non-coherent energy detection. Thus, it may increase the design complexity. The MRC receiver combines all the diversity branches weighted with their corresponding complex fading gains as shown in Figure two.

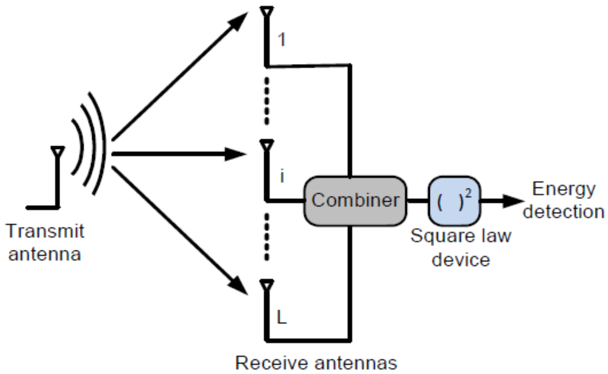

Figure 2: Energy detection with MRC scheme.

The energy detector processes the samples of the combined signal of L diversity branches, $Y(n)$, which can be given as

$$Y(n) = Hs(n) + W(n) \quad (25)$$

where $H = \sum_{l=1}^{L} |h_l|^2$ and $W(n) = \sum_{l=1}^{L} h_l^* w_l(n)$ are effective channel gain and noise sample, respectively, and $w_l(n)$ and h_l are noise and channel coefficient of the lth branch, respectively. The output signal of the MRC can be written as (25).

Thus the test statistic is given as

$$\Lambda = \sum_{n=1}^{N} |Y(n)|^2 \quad (26)$$

The effective number of samples for the test statistic is N. The instantaneous SNR of the combiner output is thus $\gamma^{MRC} = \gamma_1 + \gamma_2 + - - - - \gamma_L$. Since energy detector compares the received energy after the L independent and identically distributed(i.i.d) branches are combined, the expression of the false-alarm probability is same as (2) and the instantaneous detection probability for AWGN channels can be given as $P_d = Q_N\left(\sqrt{2N\gamma^{MRC}}, \sqrt{\lambda}\right)$. To derive the average detection probability, P_d should then be averaged over the Rayleigh fading first, and then averaged over the shadowing. The PDF of γ^{MRC} for i.i.d Rayleigh fading channels is given by [25]

$$f_{\gamma^{MRC}}(x) = \frac{x^{L-1} e^{-\frac{x}{\bar{\gamma}}}}{\Gamma(L)\bar{\gamma}^L} \quad (27)$$

where $\bar{\gamma}$ is the average SNR in any branch (note that the "averaging" is on fading only, excluding shadowing). The $f_\gamma MRC(x)$ in (27) is similar to the PDF of γ under Nakagami fading in no-diversity. Therefore, after averaging on Rayleigh fading, the P_d under MRC $(P_d{}^{MRC})$ can be obtained from the average detection probability for a Nakagami channel with no diversity.

ii. Selection Combining

In the SC diversity scheme, the branch with maximum SNR, γ_{max} is to be selected. The PDF of γ_{max} for i.i.d Rayleigh branches is known to be given by

$$f_{\gamma^{max}}(\gamma) = \frac{L}{\bar{\gamma}}(1 - e^{-\gamma/\bar{\gamma}})^{L-1} e^{-\gamma/\bar{\gamma}} \quad (28)$$

This PDF can be rewritten as

$$f_{\gamma^{max}}(\gamma) = L \sum_{i=0}^{L-1} \frac{(-1)^i}{i+1} \binom{L-1}{i} \frac{1}{\bar{\gamma}/(i+1)} e^{-\frac{\gamma}{\bar{\gamma}/(i+1)}} \quad (29)$$

The PDF in (29) represents a weighted sum of exponential variates each with parameters $\frac{\bar{\gamma}}{i+1}$. Hence, the average P_d for the SC diversity scheme, $\bar{P}_{d\ SC}$ can be evaluated as

$$\bar{P}_{d\ SC} = L \sum_{i=0}^{L-1} \frac{(-1)^i}{i+1} \binom{L-1}{i} \bar{P}_{d\ Ray}\left(\frac{\bar{\gamma}}{i+1}\right) \quad (30)$$

Where $\overline{P_{d_{RAY}}}\left[\frac{\bar{\gamma}}{i+1}\right]$ is the $\overline{P_{d_{RAY}}}$ obtained in (10) with the replacement of each $\bar{\gamma}$ by $\frac{\bar{\gamma}}{i+1}$

III. Simulation Results and Discussions:

An extensive set of simulations have been conducted in MATLAB using the system model as described in the previous section. The emphasis is to analyze the performance of energy based spectrum sensing techniques in different fading channel. The result is conducted on the basis of probability of false alarm and probability of detection under different SNR in different channels.

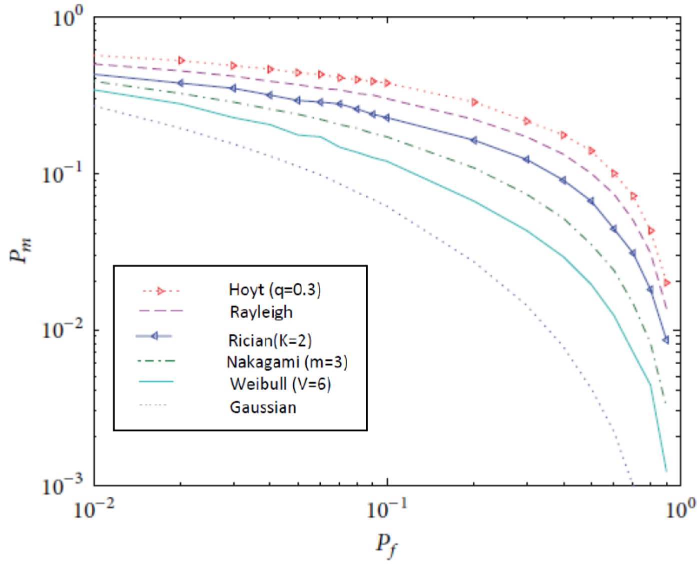

Figure 3: Complementary Receiving operating characteristics (CROC) curves for different fading

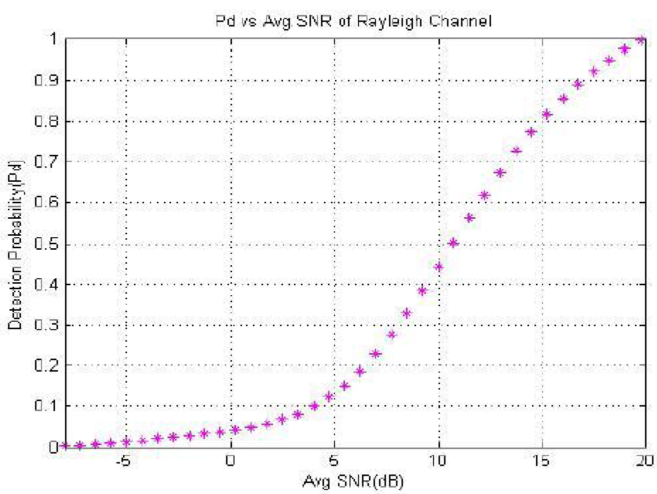

Figure 4: Probabbility of detection (P_d) vs average SNR ($\bar{\gamma}$) for Rayleigh fading Channel.

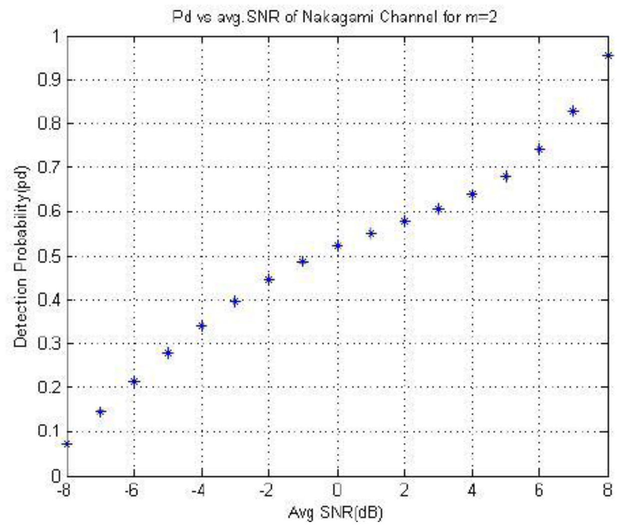

Figure 5: Probability of detection (P_d) vs average SNR ($\bar{\gamma}$) for Nakagami Channel.

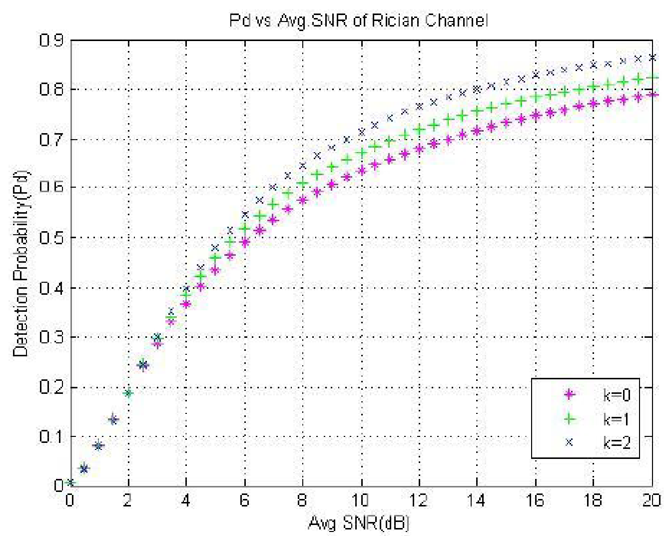

Figure 6: Probability of detection (P_d) vs average SNR ($\bar{\gamma}$) for Rician Channel

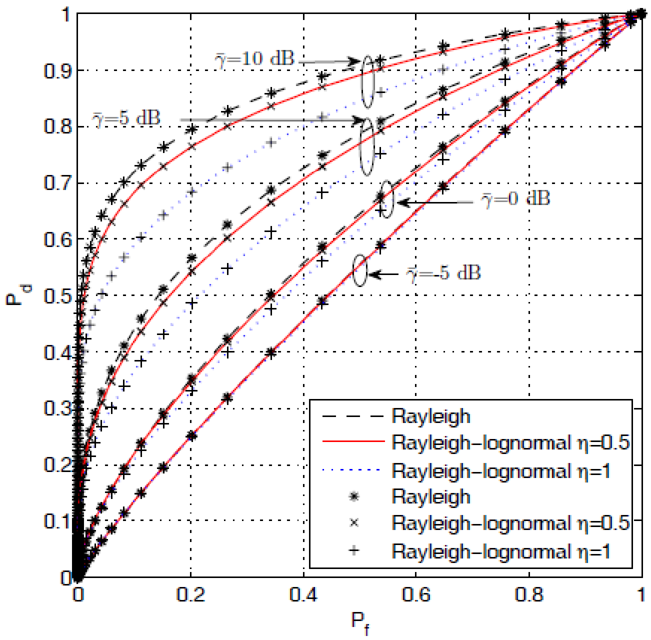

Figure 7: ROC curves of an energy detector over Rayleigh and Rayleigh- lognormal fading channels

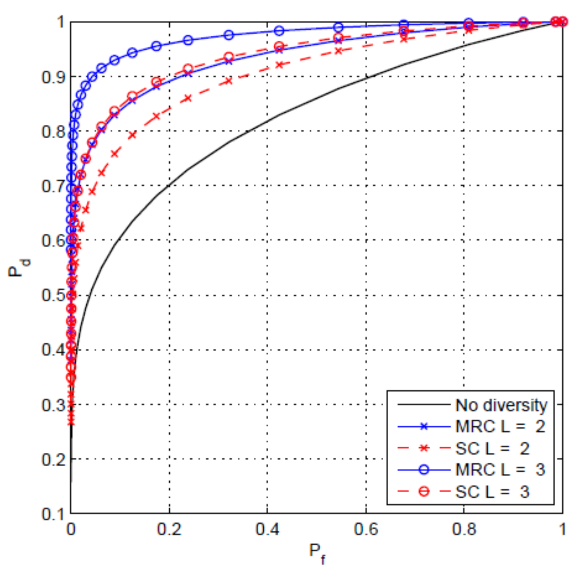

Figure 8: ROC curves for L -branch MRC diversity and SC diversity receptions

Figure 3 shows complementary ROC curves for spectrum sensing in the presence of Hoyt, Rayleigh, Rician, Nakagami-m, and Weibull fading channels. Hoyt, Rician, Nakagami-m, and Weibull fading parameters are assumed to be $q = 0.3$,$K = 2$,$m = 3$, and$V = 6$, respectively. Comparing the AWGN curve with those corresponding to fading, we observe that spectrum sensing performance degrades in the presence of fading. The performance of energy detector is the best in Weibull fading channel among all fading channels. In figure 4 the plot of detection probability vs average SNR is shown where the detection probability increases as average SNR increases. It is the case for Rayleigh fading channel where no diversity technique is applied.

In figure 5 the similar plot is shown for Nakagami channel which reflects that Nakagami channel has better performance than Rayleigh channel at low SNR values. Figure 6 shows the similar plot for Rician channel for different values of the Rician factor k. It shows that the detection probability increases as the Rician factor increases for a given SNR value. Figure 7 iilustrates illustrates ROC curves for small scale fading with Rayleigh channel and composite fading (multipath and shadowing) with Rayleigh-lognormal channel. The energy detector capabilities degrade rapidly when the average SNR of the channel decreases from 10 dB to -5 dB. Further, there is a significant performance degradation of the energy detector due to the shadowing effect in higher average SNR.

The performance of MRC and SC diversity schemes with different number L of diversity branches, which have the same instantaneous shadowing, is illustrated in Figure 8 .There is an obvious diversity gain in the case of diversity systems compared to no-diversity system . It is clear from the figure that MRC always outperforms SC.

IV. CONCLUSION

The energy based techniques for spectrum sensing in cognitive radio over composite channels have been investigated. It is shown that the spectrum sensing employed in the cognitive radio network depends upon channel distributions. The performance of spectrum sensing in Weibull fading channel outperforms that of any other fading channel considered in this paper. Although the Rayleigh and Rayleigh-lognormal fading channels are considered here, the same analytical framework can be extended to Nakagami-m and Nakagami-lognormal fading channels with integer fading parameter m.Furthermore, diversity receptions such as MRC and SC are used to boost the performance of the energy detector.The ROC reveals the effect of diversity advantage, and, as expected, MRC improves the performance of the energy detector more than SC. This paper focuses diversity techniques only to Rayleigh fading channel. The same can be extended to Rician and Nakagami channels also.

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