Energy Detection Based Spectrum Sensing Over Wireless Fading Channels In Cognitive Radio Network

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Abstract

The rapid growth of wireless communications has made the problem of under utilization of spectrum. Cognitive Radio technology has come out to solve this problem by allowing unlicensed user to use licensed spectrum bands opportunistically without affecting their performance. To sense existence of licensed user, Energy Detection based spectrum sensing technique is used over different wireless fading channels. Performance metrics like probability of false alarm, probability of detection and signal to noise ratio are evaluated by analyzing receiver operating characteristics. This paper presents a simulation comparison among different wireless fading channels. The results show that probability of detection is improved in all fading channels and Nakagami-m fading channels gives more improved performance than other fading channels by using Energy Detection Spectrum Sensing Technique.

1. Introduction

Traditional wireless networks use fixed spectrum allocation policies for licensed users. Recent studies on the measurement of the spectrum show that by conventional spectrum an allocation policy, the average utilization of the spectrum is low as illustrated in Figure 1 [1], [2]. And this underutilization is due to the fact that a licensed user may not fully utilize the spectrum at all times in all locations. Hence to meet the increasing spectrum demands for wireless applications, needs of flexible spectrum management technique are arises in order to improve efficiency of spectrum. Dynamic Spectrum access is proposed to solve these current inefficiency problems and hence Cognitive Radio (CR) is the key enabling technology which will enable the user to determine which portion of spectrum is available and detect presence of licensed users when user is operated in licensed band (*i.e.* Spectrum Sensing). CR detect unused spectrum and share spectrum without harmful interference with other users. To sense the existence of licensed user, Spectrum

Sensing techniques are used. This paper is aimed to discuss Energy detection based Spectrum Sensing Technique over different Wireless Fading Channel and analyze improvement in signal detection capability.
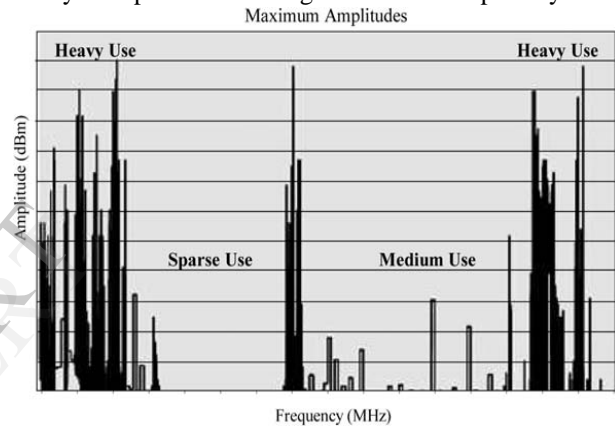

Figure 1 Spectrum under-utilization

A number of schemes related to Energy detection based spectrum sensing have been investigated in the literature. The problem of detecting an unknown deterministic signal over a flat band limited Gaussian noise channel was first addressed by Urkowitz [3]. By using Shanon's sampling formula, the problem of the detection of a deterministic signal in white Gaussian noise, by means of an energy measuring device, reduces to the consideration of the sum of these squares of statistically independent Gaussian variables. When the signal is absent, the decision statistic has a central chi-square distribution with the same numbers of degrees of freedom equal to twice the time-bandwidth product of the input. When the signal is present, the decision statistics has non-central chi-square distribution with the same number of degrees of freedom and a non-centrality parameter λ equal to ratio of signal to two-sided noise spectral density. In [4], author looked into the performance of spectrum sensing based on spectrum estimation. Mathematical expressions are derived for the probability of false alarm, and the probability of miss for i.i.d Rayleigh and Rician channels. The provided expressions were

confirmed by the corresponding Monte Carlo simulation results. In comparison with time-domain energy detection, we find that the probability of false alarm at a specific frequency is not affected by changing the observations length. Similarly, the probability of missed detection is not affected by the change of vector length when all other parameters are fixed. In addition, the results have revealed that, in comparison with the conventional energy detector, the studied frequency domain technique yields significant performance enhancement in the form of reduced probability of false alarm. The performance of energy detector is characterized by Receiver Operating curves usually. S. Atapattu et al. [5] used AOC (Area under the Receiver Operating curves) to analyze the performance of the energy detector method over Nakagami fading channels. Results showed that a higher value of fading parameter leads to larger average AUC, and thus, higher overall detection capability. This is because the average AUC converges to unity faster when the average SNR and the fading index increase Also, amongst the average SNR and the fading parameter, the average SNR is shown to be the dominant factor in determining the detection capability, particularly in the low-SNR region. Mohammad Hossain *et.al.* [6] analyzed the performance of cooperative spectrum sensing for different number of Cognitive Radio users in Cognitive Radio. Performance of cooperative spectrum sensing over Rayleigh and Nakagami fading are presented and compared. It has been found that probability of missed detection is decreased by using different number of CR users. It is observed that OR rule gives better performance than AND and MAJORITY rule in various channels. Also it is observed that spectrum sensing for different number of CR users is harder in presence of Rayleigh and Nakagami fading and performance of energy detection degrades more in Nakagami channels than Rayleigh channel. In [7], the performance of energy detection based spectrum sensing in multipath fading environment is analyzed using OFDM multiplexing technique. A predetermined value of probability of detection and probability of false Alarm is used in order to calculate the optimum threshold value. That threshold value is used to evaluate the performance in the sense of probability of detection Vs SNR. This is known as Constant detection rates (CDR) and Constant False Alarm rates (CFAR). In real time scenarios the noise variance is unknown therefore both known and unknown noise variance cases are also discussed.

The main objective of the Project is to study and evaluate closed form expressions for probability of detection for various fading channels like additive white Gaussian noise (AWGN), Rayleigh and Nakagami. Also this project gives primitive objective is to study and analyze performance of energy detection based spectrum sensing technique using receiver operating characteristics curve (ROC).

The paper is organized as follows: Section 2 explains System Modeling for Energy detection based Spectrum Sensing in which closed form expressions for Probability of Detection for various Fading Channels are evaluated. Simulation results for different fading channels are presented in Section 3. Finally the report is concluded in Section 4 that highlights the applications that merit attention in future scope for development.

2. System Modeling

Energy detection is the most popular spectrum sensing method since it is simple to implement and does not require any prior information about the primary signal [8]. An energy detector (ED) simply treats the primary signal as noise and decides on the presence or absence of the primary signal based on the energy of the observed signal. Since it does not need any a priori knowledge of the primary signal, the ED is robust to the variation of the primary signal. Moreover, the ED does not involve complicated signal processing and has low complexity. In practice, energy detection is especially suitable for wide-band spectrum sensing [9]. Energy detector is composed of four main blocks as shown in Figure 2 [10].
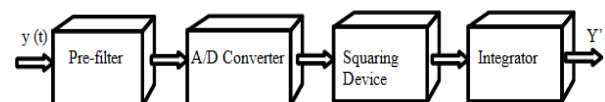
Figure 2 Block Diagram of Energy Detection Based Spectrum Sensing

The output that comes out of the integrator is energy of the filtered received signal over the time interval T and this output is considered as the test statistic to test the two hypotheses H_0 and H_1 [3]. H_0: corresponds to the absence of the signal and presence of only noise. H_1: corresponds to the presence of both signal and noise.

Thus for the two state hypotheses numbers of important cases are:-

a) H1 turns out to be TRUE in case of presence of primary user i.e. P (H1 / H1) is known as Probability of Detection (P_d).

b) H0 turns out to be TRUE in case of presence of primary user i.e. P (H0 / H1) is known as Probability of Missed-Detection (P_m).

c) H1 turns out to be TRUE in case of absence of

primary user i.e. P (H1 / H0) is known as Probability of False Alarm (P_f).

2.1 Decision Statistic

Considering the following notations: $x\ (t)$ is the transmitted signal waveform, $y\ (t)$ is the received signal waveform, $w_i\ (t)$ is in-phase noise component, $w_q\ (t)$ is quadrature phase component, B_N is noise bandwidth, N_0 is power-spectral density (two-sided), N is power spectral density (one-sided), T is the sampling interval, E_s is the signal energy, Λ is decision threshold. The received signal $y\ (t)$ is filtered by a pre-filter which is a b a n d - p a s s filter. The filtered signal is then passed through A/D converter i.e. converted to samples. Decision statistic can be Y or any quantity which is monotonic with Y. Taking Y' as decision statistic [3].

$$Y' = \frac{1}{N_0}\int_0^T y^2(t)dt \qquad (1)$$

Decision statistic Y' under H_1 has a non-central chi-square distributed [11] with $2B_NT$ degrees of freedom and non-centrality parameter λ given by $\frac{E_s}{N_0}$ [3]. Now, defining Signal to Noise Ratio (SNR), γ in terms of non-centrality parameter as in [12],

$$\gamma = \frac{E_s}{N} = \frac{E_s}{2N_0} = \frac{\lambda}{2} \qquad (2)$$

2.2 Probability of detection for AWGN Channel

Probability of detection P_d and false alarm P_f can be evaluated respectively by [12],

$$P_d = P(Y' > \Lambda|H_1) \qquad (3)$$

$$P_f = P(Y' > \Lambda|H_0) \qquad (4)$$

Where Λ is decision threshold, Also, P_f can be written in terms of Probability density function as [13],

$$P_f = \int_\Lambda^\infty f_{Y'}(y)dy \qquad (5)$$

From (4), we get:

$$P_f = \frac{1}{2^d\,\Gamma(d)}\int_\Lambda^\infty y^{d-1}e^{-\left(\frac{y}{2}\right)}dy \qquad (6)$$

Dividing and multiplying the RHS of above equation by 2^{d-1}, we get,

$$P_f = \frac{1}{2\,\Gamma(d)}\int_\Lambda^\infty \left(\frac{y}{2}\right)^{d-1}e^{-\left(\frac{y}{2}\right)}dy \qquad (7)$$

Substituting $\frac{y}{2} = t$, $\frac{dy}{2} = dt$ and changing the limits of integration to $\left(\frac{\Lambda}{2},\infty\right)$, we get,

$$P_f = \frac{1}{2\,\Gamma(d)}\int_{\Lambda/2}^\infty t^{d-1}e^{-(t)}dt \qquad (8)$$

or

$$P_f = \frac{\Gamma(d,\Lambda/2)}{\Gamma(d)} \qquad (9)$$

where $\Gamma\ (.)$ is the incomplete gamma function [14]. Now, probability of detection can be written by making use of cumulative distribution function [13].

$$P_d = 1 - F_{Y'}(\Lambda) \qquad (10)$$

The cumulative distribution function (CDF) of Y' can be obtained (for an even number of degrees of freedom which is 2d in this case) as [11],

$$F_{Y'}(y) = 1 - Q_d(\sqrt{\lambda},\sqrt{\Lambda}) \qquad (11)$$

Therefore using (10) and (11), probability of detection P_d for AWGN channel is [12],

$$P_d = Q_d(\sqrt{\lambda},\sqrt{\Lambda}) \qquad (12)$$

Using (2) $\qquad P_d = Q_d(\sqrt{2\gamma},\sqrt{\Lambda}) \qquad (13)$

Where, $Q_d(.,.)$ is the generalized Marcum-Q function and thus, probability of detection for AWGN channel can be evaluated using above expression.

2.3 Probability of detection for Rayleigh Channel

Probability density function for Rayleigh channel is [15],

$$f(\gamma) = \frac{1}{\bar{\gamma}}\exp\left(\frac{-\gamma}{\bar{\gamma}}\right) \qquad,\qquad \gamma \geq 0 \qquad (14)$$

Probability of detection for Rayleigh Channel is obtained by averaging their probability density function over Probability of detection for AWGN Channel [12],

$$P_{d,R} = \int_0^\infty P_d f(\gamma) d\gamma \qquad (15)$$

Where $P_{d,R}$ is the probability of detection for Rayleigh Channel. With (13), (14) and (15) becomes:

$$P_{d,R} = \frac{1}{\bar{\gamma}} \int_0^\infty Q_d(\sqrt{2\gamma}, \sqrt{\Lambda}) \exp\left(\frac{-\gamma}{\bar{\gamma}}\right) d\gamma \qquad (16)$$

Now substituting $\sqrt{\gamma} = x, \gamma = x^2, d\gamma = 2xdx$ in (16), we get,

$$P_{d,R} = \frac{2}{\bar{\gamma}} \int_0^\infty x. Q_d(\sqrt{2}x, \sqrt{\Lambda}) \exp\left(\frac{-x^2}{\bar{\gamma}}\right) dx \qquad (17)$$

Considering result in [16],

$$\int_0^\infty dx.x. \exp\left(\frac{-p^2 x^2}{2}\right) Q_M(ax,b) = \frac{1}{p^2}. \exp\left(\frac{-b^2}{2}\right). \left\{ \left(\frac{p^2+a^2}{a^2} \right)^{M-1} \right.$$
$$\left[\exp\left(\frac{b^2}{2}.\frac{a^2}{p^2+a^2} \right) - \sum_{n=0}^{M-2} \frac{1}{n!} \left(\frac{b^2}{2}.\frac{a^2}{p^2+a^2} \right)^n \right] + \sum_{n=0}^{M-2} \frac{1}{n!} \left(\frac{b^2}{2} \right)^n \right\}$$

$$(18)$$

Comparing (17) and (18),

$$p^2 = \frac{2}{\bar{\gamma}}, \; a = \sqrt{2} b = \sqrt{\Lambda}, \text{ and } M = d .$$

Thus, using (18) Probability of detection for Rayleigh Channel can be expressed as [12],

$$P_{d,R} = e^{(-\Lambda/2)} \sum_{n=0}^{d-2} \frac{1}{n!} \left(\frac{\Lambda}{2} \right)^n +$$
$$\left(\frac{1+\bar{\gamma}}{\bar{\gamma}} \right) \left[\exp\left(-\frac{\Lambda}{2(1+\bar{\gamma})} \right) - \exp\left(-\frac{\Lambda}{2} \right) \sum_{n=0}^{d-2} \frac{1}{n!} \left(\frac{\Lambda\bar{\gamma}}{2(1+\bar{\gamma})} \right)^n \right] \qquad (19)$$

The above expression gives the probability of detection for Energy detection based spectrum sensing over Rayleigh Channel.

2.4 Probability of detection for Nakagami-m fading Channel

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;

$$K = \frac{\sqrt{m^2-m}}{m-\sqrt{m^2-m}}, \qquad m > 1 \qquad (20)$$

$$m = \frac{(K+1)^2}{(2K+1)} \qquad (21)$$

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 [17], can be written as

$$Q_d(\sqrt{2\gamma}, \sqrt{\lambda}) = \sum_{n=0}^\infty \frac{\gamma^n e^{-\gamma}}{n!} \sum_{k=0}^{n+u-1} \frac{e^{-\frac{\lambda}{2}}}{k!} \left(\frac{\lambda}{2} \right)^k \qquad (22)$$

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

$$f(\gamma) = \frac{1}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}} \right)^m \gamma^{m-1} \exp\left(-\frac{m\gamma}{\bar{\gamma}} \right) \qquad , \gamma \geq 0 \quad (23)$$

where, m is the Nakagami parameter. The average P_d in case of Nakagami Channels $\bar{P}_{d\,Nak}$ can now be obtained by averaging (13) over (23) and then using again the change of variable $x = \sqrt{2\gamma}$ yielding,

$$\bar{P}_{d\,Nak} = a \int_0^\infty x^{2m-1} \exp\left(-\frac{mx^2}{2\bar{\gamma}} \right) Q_d(x, \sqrt{\lambda}) dx \qquad (24)$$

where, $$a = \frac{1}{\Gamma(m)2^{m-1}} \left(\frac{m}{\bar{\gamma}} \right)^m \qquad (25)$$

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

$$\bar{P}_{d\,Nak} = a \left[G_1 + \beta \sum_{n=1}^{u-1} \frac{(\lambda/2)}{2(n!)} {}_1 F_1\left(m; n+1; \frac{\lambda}{2} \frac{\bar{\gamma}}{m+\bar{\gamma}} \right) \right] (26)$$

where, $_1F_1(.;.;.)$ is the confluent hypergeometric function [18].

$$\beta = \Gamma(m)\left(\frac{2\bar{\gamma}}{m+\bar{\gamma}}\right)^m e^{-\lambda/2} \qquad (27)$$

and $\quad G_1 = \int_0^\infty x^{2m-1}\exp\left(\frac{-mx2}{2\bar{\gamma}}\right)Q_d(x,\sqrt{\lambda})dx \qquad (28)$

Where Q(.,.) is the first order Marcum Q-function. G_1 can be evaluated for inter m with aid of [14].

$$G_1 = \frac{2^{m-1}(m-1)!}{\left(\frac{m}{\bar{\gamma}}\right)^m}\frac{\bar{\gamma}}{m+\bar{\gamma}}e^{(-\lambda/2).\frac{m}{m+\bar{\gamma}}}\left|\left(1+\frac{m}{\bar{\gamma}}\right)\left(\frac{m}{m+\bar{\gamma}}\right)^{m-1}L_{m-1}\left(-\frac{\lambda}{2}\frac{\bar{\gamma}}{m+\bar{\gamma}}\right)\right.$$

$$\left.+\sum_{n=0}^{m-2}\left(\frac{m}{m+\bar{\gamma}}\right)^n L_n\left(-\frac{\lambda}{2}\frac{\bar{\gamma}}{m+\bar{\gamma}}\right)\right|$$

$$(29)$$

Where, L_n is the Laguerre polynomial of degree n.

3. Simulation Result

Detection probability (P_d), False alarm probability (P_f) and missed detection probability $(P_{md} = 1 - P_d)$ are the key measurement metrics that are used to analyze the performance of spectrum sensing techniques. The performance of a spectrum sensing technique is illustrated by the receiver operating characteristics (ROC) curve which is a plot of P_d versus P_f or P_{md} versus P_f. All simulation was done on MATLAB version 7.10.0 (R2010a) over three different fading channels *viz*. AWGN, Rayleigh and Nakagami Channels. Monte-Carlo method is used for simulation. We described receiver through it complimentary ROC curves for a different values of probability of false alarm, probability of detection and signal to noise ratio.

From Figure 3-5, it is clearly seen that, for vey less probability of false alarm values, probability of missed detection is very high. But, as P_f values are getting increased, P_{md} values are going to reduce drastically. Thus, it improves performance of energy detector at low SNR values. Table 1 show that values of probability of false alarm increases; there is drastic decrease in probability of missed detection. Similarly, as values of SNR are varying there is still decrease in values of probability of missed detection.
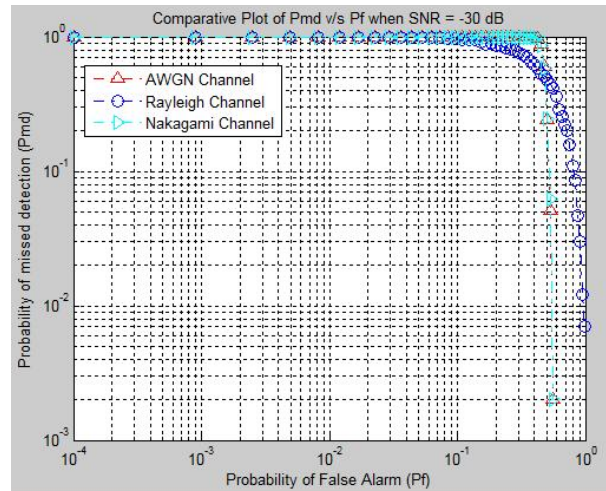

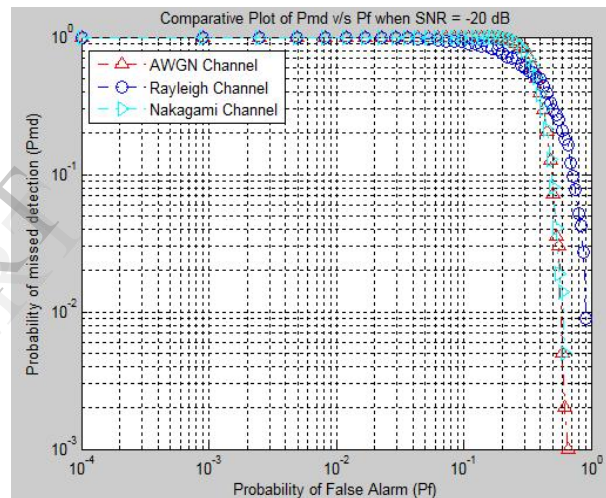**Figure 3 Complementary ROC Curve when SNR = - 30 dB**

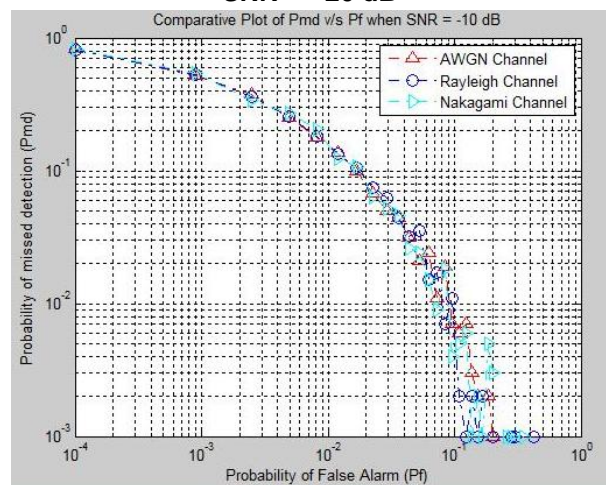**Figure 4 Complementary ROC Curve when SNR = - 20 dB**

Figure 5 Complementary ROC Curve when SNR = - 10 dB

Table 1: Comparison of Probability of missed detection (P_{md}) versus Probability of false alarm (P_f) when SNR is varying over different Wireless Fading Channels

Value of P_f	AWGN			Rayleigh			Nakagami		
	Probability of missed detection			Probability of missed detection			Probability of missed detection		
	SNR = -30dB	SNR = -20dB	SNR = -10dB	SNR = -30dB	SNR = -20dB	SNR = -10dB	SNR = -30dB	SNR = -20dB	SNR = -10dB
0.0001	1	1	0.821	1	1	0.804	1	1	0.826
0.1521	1	0.999	0.002	0.92	0.852	0.001	1	0.999	0.002
0.3969	0.999	0.393	0	0.623	0.496	0	0.999	0.381	0
0.4761	0.593	0.125	0	0.505	0.333	0	0.583	0.13	0
0.5329	0.051	0.035	0	0.441	0.271	0	0.062	0.041	0

Table 2: Comparison of Probability of detection (P_d) versus Probability of false alarm (P_f) when SNR is varying over different Wireless Fading Channels

Value of P_f	AWGN			Rayleigh			Nakagami		
	Probability of detection			Probability of detection			Probability of detection		
	SNR = -30dB	SNR = -20dB	SNR = -10dB	SNR = -30dB	SNR = -20dB	SNR = -10dB	SNR = -30dB	SNR = -20dB	SNR = -10dB
0.0049	0.004	0.139	0.754	0.026	0.178	0.768	0.003	0.147	0.747
0.0225	0.055	0.46	0.944	0.153	0.498	0.931	0.056	0.508	0.925
0.0625	0.28	0.767	0.978	0.336	0.735	0.984	0.296	0.767	0.983
0.1369	0.624	0.922	0.998	0.572	0.895	0.999	0.607	0.92	0.996
0.2401	0.873	0.982	0.999	0.751	0.96	1	0.889	0.984	0.998

Table 3: Comparison of Probability of detection (P_d) versus Signal to Noise Ratio (SNR) when Probability of false alarm (P_f) is varying over different Wireless Fading Channels

Value of SNR (in dB)	AWGN			Rayleigh			Nakagami		
	Probability of detection			Probability of detection			Probability of detection		
	P_f = 0.001	P_f = 0.003	P_f = 0.005	P_f = 0.001	P_f = 0.003	P_f = 0.005	P_f = 0.001	P_f = 0.003	P_f = 0.005
- 15	0	0.017	0.057	0.0339	0.11	0.183	0	0	0
- 14	0.016	0.101	0.227	0.072	0.198	0.278	0	0	0
- 13	0.101	0.295	0.442	0.144	0.345	0.481	0	0	0
- 12	0.283	0.555	0.721	0.329	0.507	0.673	0	1	1
- 11	0.55	0.804	0.894	0.575	0.786	0.864	1	1	1
- 10	0.844	0.957	0.978	0.86	0.937	0.874	1	1	1

From Figure 6-8 and table 2, it is depicted that as values of probability of false alarm increases, values for probability of detection also increases. When values of SNR are increased, then there is dramatically increase observed in probability of detection at very few values of probability of false alarm. As SNR values vary from -14 dB to -12 dB, probability of detection improves by 1.77 times in AWGN channel, by 1.95 times in Rayleigh Channel and by 1.84 times in case of Nakagami Channel.

From Figure 9-11 and table 3, it is clearly seen that as values of signal to noise ratio increases, values for probability of detection also increases. When values are drawn for constant probability of false alarm and P_f

increases, there is improvement in probability of detection observed. As values of P_f vary from 0.01 to 0.05, there is drastic improvement in probability of detection by 6.4 times in AWGN, 5.7 times in Rayleigh and 7.86 times in case of Nakagami Channel. Thus, by Monte-Carlo simulation method, it is observed that performance of energy detection based spectrum sensing is boosted up in Nakagami Channel compared with others.

4. Conclusion

In this paper, dynamic spectrum management techniques like Cognitive Radio Technology have been discussed. Performance of Energy detection based
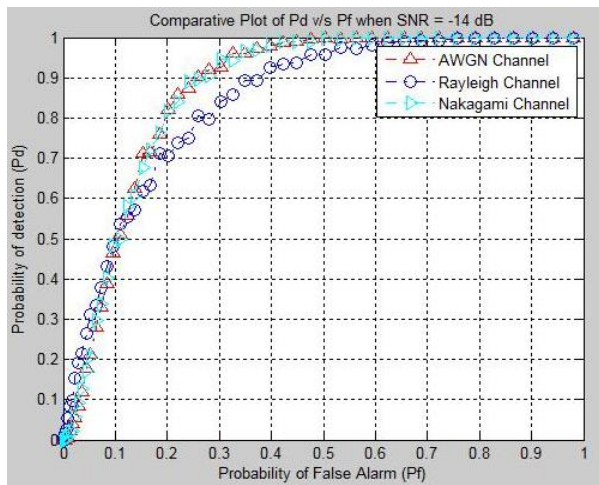
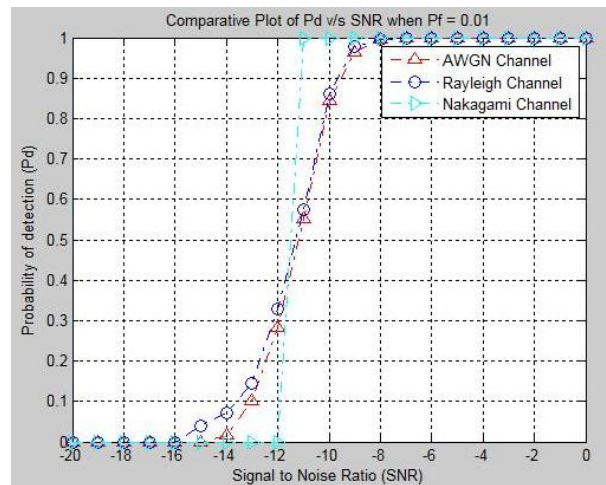**Figure 6 ROC Curve when SNR = - 14 dB**
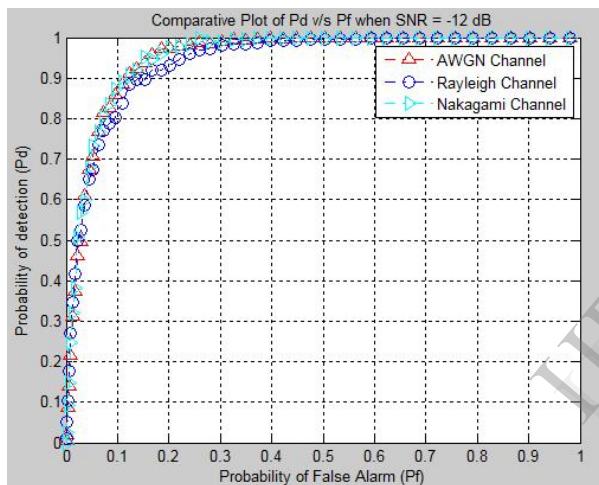

Figure 9 Plot of P$_d$ v/s SNR when P$_f$ = 0.01
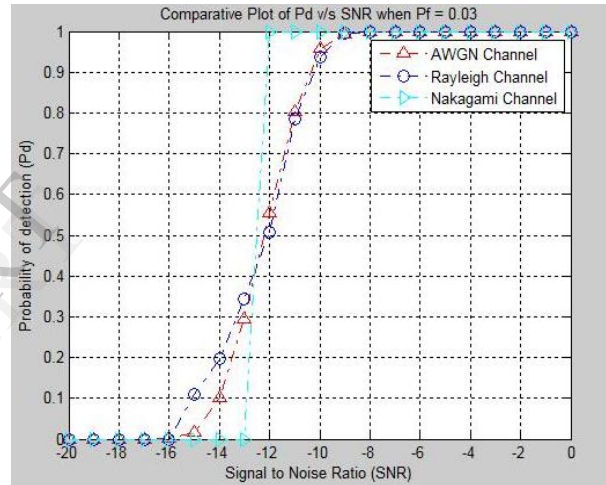

Figure 7 ROC Curve when SNR = - 12 dB

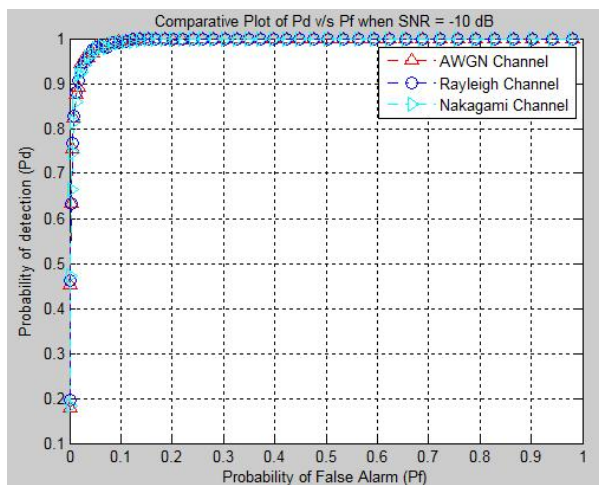**Figure 10 Plot of P$_d$ v/s SNR when P$_f$ = 0.03**

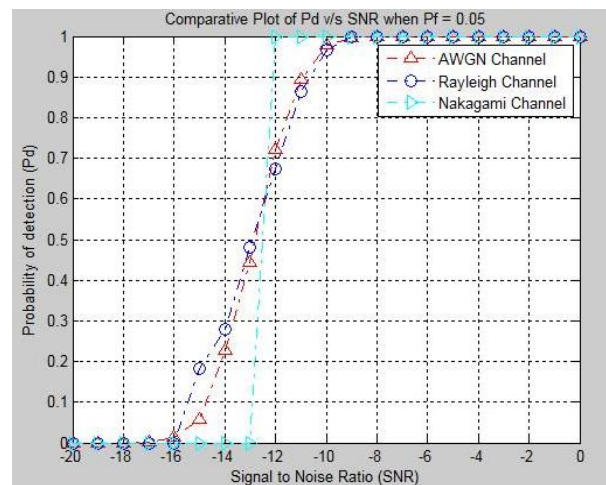

Figure 8 ROC Curve when SNR = - 10 dB

Figure 11 Plot of P$_d$ v/s SNR when P$_f$ = 0.05

Spectrum Sensing is implemented over Wireless Fading channels *viz.* AWGN, Rayleigh and Nakagami

– m fading channels. Closed form expressions for probability of detection and false alarm over different wireless fading channels are evaluated. Three performance metrics such as probability of detection, probability of false alarm and signal to noise ratio are considered for analysis for energy detection based spectrum sensing technique. Various ROC (Receiver Operating Characteristics) curves *i.e.* plot of P_d versus P_f or P_{md} versus P_f has been plotted over fading channels. Monte-Carlo technique is used for simulation in MATLAB version 7.10.0.499 (R2010a) as a software platform.

As values of SNR vary from -30 dB to -10 dB, probability of detection improves by 1.77 times in AWGN Channel, 1.95 times in Rayleigh Channel and 1.84 times in Nakagami-m fading channels. Also, when probability of false alarm increases from 0.01 to 0.05, there is drastic improvement observed in probability of detection by 6.4 times in AWGN Channel, 5.7 times in Rayleigh Channel and 7.86 times in case of Nakagami –m fading channels. Thus in Cognitive Radio Network, it is observed that with low computational complexities, detection of presence of primary user signal is easiest job by using Energy detection based Spectrum sensing technique. From comparative plot, it is clearly observed that, among various fading channels Nakagami–m fading channels gives more improvement in probability of detection than Rayleigh and AWGN fading channels.

4.1 Future Scope

In future, performance analysis can be done over other wireless fading channels like Rician, Suzuki etc. Also, cooperative spectrum sensing method can be used to achieve still better sensing performance in detector of Cognitive Radio Network.

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