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Performance Comparison of the Standard Transmitter Energy Detector and an Enhanced Energy Detector Techniques

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Abstract Frequency spectrum is an important natural resource that needs to be utilized efficiently. The existing static frequency allocation is not in a position to accommodate the ever increasing demand in the wireless communication and the subsequent increase in higher data rate devices. In spite of this, different researches show that most of the times the spectrum bands are not in use which seems a paradox [1], [2]. Cognitive radio (CR) is becoming the candidate technology to resolve this paradox because it provides an efficient spectrum utilization system. This is done by utilizing an efficient primary user detection that uses opportunistic spectrum sharing mechanism. To this end, different transmitter energy detection techniques have been and is being studied [3], [4]. In this work an enhanced energy detector technique is proposed and its performance is compared with the performance of standard energy detection techniques. Matlab software is used to evaluate the performances. Simulations are carried out to show the performance enhancement of the energy detector algorithm by using cross correlation of time shifted signal observations. The simulations are carried out for both AWGN and Rayleigh fading channel-using SNR of 2dB. Simulation results showed that the enhanced energy detector algorithm (technique) minimizes the probability of misdetection and improves the probability of detection under both AWGN and Rayleigh fading channels. Moreover, both receiver operating characteristics (ROC) and complementary receiver operating characteristics (CROC) plots clearly show that the performance of the standard energy detector is enhanced by this technique.

Keywords Cognitive radio, Spectrum detection, Enhanced energy detector

1. Introduction

Spectrum detection is the art of performing measurements on a part of the spectrum and forming a decision related to spectrum usage based upon the measured data. The recent rapid growth of wireless communications has made the problem of spectrum utilization ever more critical. On one hand, the increasing diversity (voice, short message, Web, and multimedia) and demand of high quality-of-service (QoS) applications have resulted in overcrowding of the allocated spectrum bands, leading to significantly reduced levels of user satisfaction. In recent years, the service providers are faced with a situation where they require a larger amount of spectrum to satisfy the increasing quality of service (QoS) requirements of the users. This has raised the interest in unlicensed spectrum access, and spectrum detection is seen as an important enabler for this. In a scenario in which there exists a licensed user (primary user), any unlicensed (secondary users) needs to ensure that the primary user is protected, i.e., no secondary user is harmfully interfering any primary user operation. Spectrum detecting can be used to detect the presence or absence of a primary user. The Institution of Electrical and Electronics Engineering (IEEE) has formed a working group (IEEE 802.22) to develop an air interface for opportunistic secondary access to the spectrum via the cognitive radio technology [5]. The guiding philosophy of cognitive radio is to allow universal maximization of the spectrum utilization insofar as the unlicensed users do not cause degradation of service upon the original license holders. In practice, the unlicensed users, (also called the cognitive users) need to monitor the spectrum activities continuously to find a suitable spectrum band for possible utilization and to avoid possible interference to the licensed users (primary users). Since the primary users have the priority of service, the above spectrum sensing by cognitive users includes detection of possible collision when a primary user becomes active in the spectrum momentarily occupied by a cognitive user and relocation of the communication channels. Spectrum sensing is based on a well known technique called signal detection.

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Various researchers have studied detection mechanisms. Determination of threshold level for minimizing spectrum-sensing error in energy detection techniques has been investigated [6], [7]. E. Visotsky, et al, studied transmission in support of dynamic spectrum sharing [8]. Comparison of different transmitter detection techniques for application in cognitive radio has also been done [3], [4]. Since one of the main requirements of CR systems is the ability to reliably detect the presence of the primary transmissions, it needs special attention and further investigations. This work concentrates on the evaluation and comparison of the performance of the standard and the enhanced energy detection techniques by considering different metrics in the real time communication system model.

This paper is organized as follows. Section 2 explains the theoretical background and the system model. Furthermore, the probability of detection (P_d) and probability of false alarm (P_f) are evaluated in section 2.1 and 2.2, respectively. Finally, simulation results are demonstrated in section 3 and concluding remarks are made in section 4.

2. Theoretical Background

Energy detection is the most common way of spectrum detection because of its low computational and implementation complexities [9]. The decision is made by comparing the decision statistics, which corresponds to energy collected in the observation time, to an appropriate threshold [10-12] that is traditionally selected from the statistics of the noise to satisfy the false alarm rate specification of the detector based on constant false alarm rate (CFAR) principle.

2.1. System Model of Energy Detection under Awgn Channel

The performance of spectrum sensing can be characterized by the probability of false alarm (Pf), probability of miss detection (P_m) and the probability of detection (Pd). The term Pf is the probability that a secondary user (SU) decides the primary user (PU) is active when the PU is actually inactive. It reflects the level of missed access opportunity for the SU. The term Pd is the probability that a SU decides that the PU is active when the PU is actually active. The probability of miss detection (Pm = 1 – Pd) indicates the level of interference introduced to the PU (Primary users) by a SU (secondary users). Typically, Pm is restricted to be below an acceptable level to protect the PU.

The system model for energy detection that is used to identify the presence or absence of primary signal is shown in Fig 1.

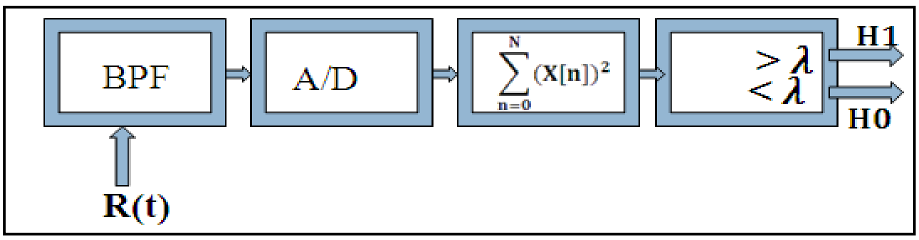

Figure 1. Block diagram of energy detector system model

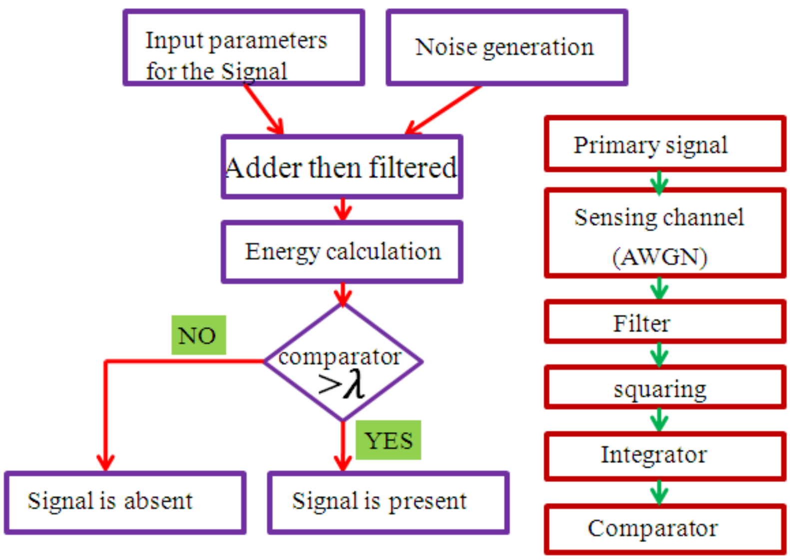

Figure 2. Flow chart for system model of energy detector

As can be seen from the figure, a band pass filter (BPF) with bandwidth W is used to limit the noise power and to normalize the noise variance. To measure the energy of the received signal, the output signal of the BPF is squared and integrated over the observation interval T. . Finally, the output of the summation (integration for continuous signal) is compared with a threshold, λ, to decide whether a licensed user is present or absent [13].

The flow chart shown in Fig. 2 describes the block diagram of Fig. 2.

The threshold value for the cost of probability of false alarm is taken to be less than or equal to 10% while different values of noise variance ranging from 0.5 to 1 are considered. At the comparator, if the energy is greater than the threshold value, it means that the transmitted signal is present and it is not possible to use the cognitive radio as a secondary user within the coverage area of the primary users. However, if the energy is less than the predefined threshold value, the primary signal is not accessing its spectrum and it is time to use the cognitive radio in an opportunistic way until the presence of the primary signal is detected.

The energy detector decides between two hypotheses H_1, which corresponds to signal plus noise, and H_0 (null hypothesis), which is the noise-only hypothesis [14]. The hypothesis model for transmitter detection is expressed as

$$R(t) = \begin{Bmatrix} n(t) \ : \ H_0 \\ s(t) + n(t) \ : \ H_1 \end{Bmatrix}, \quad (1)$$

where R(t) is the signal received by the secondary user, s(t) is the signal transmitted by the primary transmitter, and n(t) is the noise introduced by AWGN. The decision statistics Y for zero mean Gaussian distributed noise only (i.e. for H_0) follows central chi square distribution with 2TW degrees of freedom (where TW is the time-bandwidth product). On the other hand, H1 follows a non-central chi-squared distribution with 2TW degrees of freedom and non-centrality parameters 2γ (where γ is the mean SNR in the linear scale). Thus, the observation decision statistics ($Y = \sum_{n=0}^{N}(X[n])^2$, where x [n] is the output signal of the A/D) is given as [4], [15]-[17]

$$Y = \begin{Bmatrix} \chi^2{}_{2TW} \quad H_0 \\ \chi^2{}_{2TW} \ (2\gamma) \quad H_1 \end{Bmatrix} \quad (2)$$

The Probability density function (PDF) of test statistic Y of (2) can then be expressed as [13], [16], [18]

$$f_y(y) = \begin{Bmatrix} \frac{1}{2^{TW}\Gamma(TW)} y^{TW-1} e^{-\frac{y}{2}}, \quad H_0 \\ \frac{1}{2}\left(\frac{y}{2\gamma}\right)^{\frac{TW-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{TW-1}\left(\sqrt{2\gamma y}\right), \ H_1 \end{Bmatrix}, \quad (3)$$

where $\Gamma(.)$ is gamma function and $I_x(.)$ is the x^{th}-order modified Bessel functions of the first kind. The probability of detection (Pd) and false alarm (Pf) are respectively given as [19-21].

$$P_d = P_r(Y > \lambda | H1) = \quad Q_{(N=TW)}\left(\sqrt{2\gamma}, \sqrt{\lambda}\ \right) \quad (4)$$

$$P_f = P_r(Y > \lambda | Ho) = \frac{\Gamma(TW, \frac{\lambda}{2})}{\Gamma(TW)} \quad (5)$$

Subsequently, with sufficiently large values of observation (N), the distribution of the test statistic can be approximated as Gaussian distribution (using the central limit theorem) and the statistic is given by [3], [4], [13]

$$Y \approx \begin{Bmatrix} \mathcal{N}(\mu_0, {\sigma_0}^2) \ : \ Ho \\ \mathcal{N}(\mu_1, {\sigma_1}^2) \ : \ H1 \end{Bmatrix}, \quad (6)$$

where, $\mathcal{N}\ (\mu, \sigma^2)$ is Gaussian distribution with mean μ and variance σ^2. The mean and variance for both hypotheses H_0 and H_1 are given respectively as:

$$(\mu_0 = N{\sigma_n}^2\ , {\sigma_0}^2 = 2N\ {\sigma_n}^4) \quad (7)$$

and

$$(\ \mu_1 = N({\sigma_s}^2 + {\sigma_n}^2), {\sigma_1}^2 = 2N\ ({\sigma_s}^2 + {\sigma_n}^2\ )^2). \quad (8)$$

Then P_d and P_f for sufficient large value of N can be obtained using (6), (7), (8), and expressed as [12], [13]

$$P_d = Q\left(\frac{\lambda - N({\sigma_n}^2 + {\sigma_s}^2)}{\sqrt{2N({\sigma_n}^2 + {\sigma_s}^2)^2}}\right) = Q\left(\frac{\lambda - N(1+\gamma){\sigma_n}^2}{\sqrt{2N(1+2\gamma){\sigma_n}^4}}\right) \quad (9)$$

$$P_f = Q\left(\frac{\lambda - N{\sigma_n}^2}{\sqrt{2N{\sigma_n}^4}}\right) \quad (10)$$

2.2. Energy Detection under Rayleigh Fading Channel

Radio wave propagation through wireless channels is a complicated phenomenon characterized by various effects, such as multipath and shadowing. A precise mathematical description of this phenomenon is either unknown or too complex for manageable communications systems analyses. However, considerable efforts have been devoted to the statistical modeling and characterization of these different effects. When fading affects systems, the received carrier amplitude is modulated by the fading amplitude α, where α is a random variable (RV) with mean-square value $\Omega = \overline{\alpha^2}$ and probability density function (PDF) $p_\alpha(\alpha)$, which is dependent on the nature of the radio propagation environment. After passing through the fading channel, the signal is perturbed at the receiver by AWGN, which is typically assumed to be statistically independent of the fading amplitude α, and which is characterized by a one-sided power spectral density N_0 (W/Hz). Equivalently, the received instantaneous signal power is modulated by α^2. Thus we define the instantaneous SNR per symbol by $\gamma = \alpha^2 Es/N0$ and the average SNR per symbol by $\bar{\gamma} = \Omega Es/N_0$, where E_s is the energy per symbol. Our performance evaluation of digital communications over fading channels will generally be a function of the average SNR per symbol $\bar{\gamma}$. In addition, the PDF of γ is obtained by introducing a change of variables in the expression for the fading PDF, $p_\alpha(\alpha)$ of α, yielding [4], [12]:

$$p_\gamma(\gamma) = f_\gamma(\gamma) = \frac{p_\alpha\left(\sqrt{\Omega\gamma/\bar{\gamma}}\right)}{2\sqrt{\gamma\bar{\gamma}/\Omega}}. \quad (11)$$

Multipath fading (without direct line of sight) is relatively fast and frequently modeled by Rayleigh distribution. In this case the channel fading amplitude is distributed according to [12]

$$p_\alpha(\alpha) = \frac{2\alpha}{\Omega}\exp\left(-\frac{\alpha^2}{\Omega}\right), \alpha \geq 0\,. \quad (12)$$

From (1), the energy of the signal for both the H_0 and H_1 cases, under the assumption that h is Rayleigh distributed is given by [12], [13]

$$Y = \begin{Bmatrix} \chi^2{}_{2(N+1)} & : Ho \\ e_{2(\gamma^2+1)} + \chi^2{}_{2N} & : H1 \end{Bmatrix}, \quad (13)$$

where $e_{2(d^2+1)}$ is the exponential distribution with parameter $\alpha = 2(\gamma^2 + 1)$ with probability density function $f(x,\alpha) = \alpha e^{-\alpha x}$. Under the hypothesis H_0, the statistics are the same as for the AWGN channel case (Pf is independent of the SNR). However, H_1 behaves differently and has P_d given by [13], [14], [15], [18], [22]:

$$P_d = e^{-\frac{\lambda}{2}}\sum_{n=0}^{N-2}\frac{1}{n!}\left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{N-1} * \left(e^{-\frac{\lambda}{2(1+\gamma)}} - e^{-\frac{\lambda}{2}}\sum_{n=0}^{N-2}\frac{1}{n!}\left(\frac{\lambda*\bar{\gamma}}{2(1+\bar{\gamma})}\right)^n\right) \quad (14)$$

2.3. Enhanced Energy Detector

The decision statistic in normal square law energy detection involves a noise-square term that may raise the noise floor. Therefore a conventional energy detector integrating over the entire symbol period unwittingly captures the noise-only portion of the received waveform, which causes an extra noise floor. Because the noise floor increases linearly in bandwidth-time product [23], conventional energy detection is less effective to detect wide band signal.

To alleviate this problem, cross-correlation detector that correlates $R(t)$ with shifted copy is adopted here. The block diagram for cross correlation energy detection system is shown below.

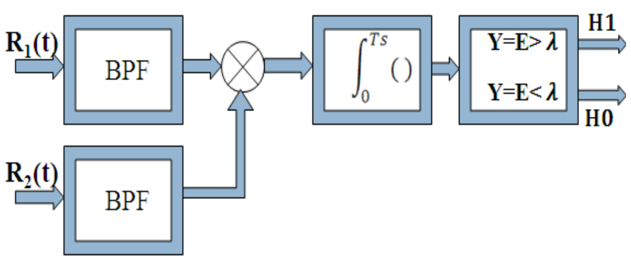

Figure 3. Block diagram of cross correlation energy detection

In signal processing, the correlation function of a random signal describes the general dependence of the values of the samples at one time on the values of the samples at another time. For continuous function, one can estimate the cross-correlation from a given interval, 0 to T_s seconds, of the sample function and the detection statistic of the enhanced energy detection is given by:

$$Y = \int_0^{T_s} R_1(t)R_2(t)\,dt \quad (15)$$

where $R_1(t)$ = s (t) + n (t) and $R_2(t)$ =s (t + Ts) + n (t + Ts). That means two observed signals at a time difference or shift of Ts are correlated. Therefore the detection statistic for the enhanced detector can be defined as [23]:

$$Y = \begin{Bmatrix} \int_0^{T_s} n(t)n(t+T_s)dt & : H_0 \\ \int_0^{T_s}\big(s(t)+n(t)\big)\big(s(t+T_s)+n(t+T_s)\big) & : H_1 \end{Bmatrix} \quad (16)$$

The noise-square term in the square law energy detector is replaced by the product of two non-overlapping segments of noise term. Notice that Y has a noise-noise term n(t)n(t + Ts) inside the integral, which causes little increase in the noise floor due to the independence between shifted noise terms, thus resulting in better detection quality. Calculation of the probability of the detection threshold requires knowledge of the probability density function (pdf) of the statistic. To facilitate receiver analysis, the pdf is approximated for sufficiently large values of N=TW. Using central limit theorem, the distribution of the test statistic can be approximated as Gaussian. Hence the statistic is given by

$$Y \sim \begin{Bmatrix} \mathcal{N}(\mu_0, \sigma_0{}^2) & : Ho \\ \mathcal{N}(\mu_1, \sigma_1{}^2) & : H1 \end{Bmatrix} \quad (17)$$

Where:

$$\begin{Bmatrix} \mu_0 = 0 \\ \sigma_0{}^2 = T_s W \sigma_n{}^2 \\ \mu_1 = T_s W \sigma_s{}^2 = N\sigma_s{}^2 \\ \sigma_1{}^2 = N(\sigma_n{}^2 + \sigma_s{}^2)^2 = T_s W(\sigma_n{}^2 + \sigma_s{}^2)^2 \end{Bmatrix}$$

From equation (4), (5), and (17), one can see variances of enhanced energy detector are half of those in traditional square law energy detector. Based on the approximate pdf, one can derive the optimal decision threshold λ. The figure of merit is the probability of detection P_d for a fixed probability of false alarms P_f. For a Gaussian pdf, the probability of false alarm and probability of detection can be expressed, respectively as [23]

$$P_f = Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right), and$$

$$P_d = 1 - Q\left(\frac{\mu_1 - \lambda}{\sigma_1}\right) \quad (18)$$

where, Q (.) is the complementary error function and the optimal threshold, λ, is by

$$\lambda = \sigma_0 Q^{-1}(P_f) + \mu_{0.} \quad (19)$$

3. Simulation Results and Discussion

In this section some results of our work are presented. All simulations are carried out under the consideration of required P_d of 90%, P_f of 10% and Pm of 10% within the bandwidth of 6MHz. The following table shows the simulation parameters considered in this work.

Table 1. Simulation parameters used for spectrum detector performance evaluation

No.	Simulation parameters	Types and value
1	Interference signal	AWGN
2	Bandwidth (W)	6MHz
3	Modulation	BPSK
4	Channel	AWGN & Rayleigh
5	Noise variance (${\sigma_n}^2$)	Varies from 0.5 to 1
6	Noise uncertainty (ρ)	Varies from 0 to 5dB
7	Number of observations (N)	10-100
8	Number of secondary nodes (Ns=n)	1-10

3.1. Simulation Results for the Standard Energy Detector

Fig. 4 and Fig. 5 present P_d and P_m versus threshold under AWGN channel for different SNR values respectively. The threshold values are defined based on the noise variance and probability of false alarm using Constant False Alarm Rate (CFAR). As one can observe from the results, P_d is inversely proportional to the threshold whereas P_m is directly proportional to the threshold. For minimum value of threshold, it is possible to achieve better detection performance. But the performance of the energy detector deteriorates when the received signal to noise ratio decreases.

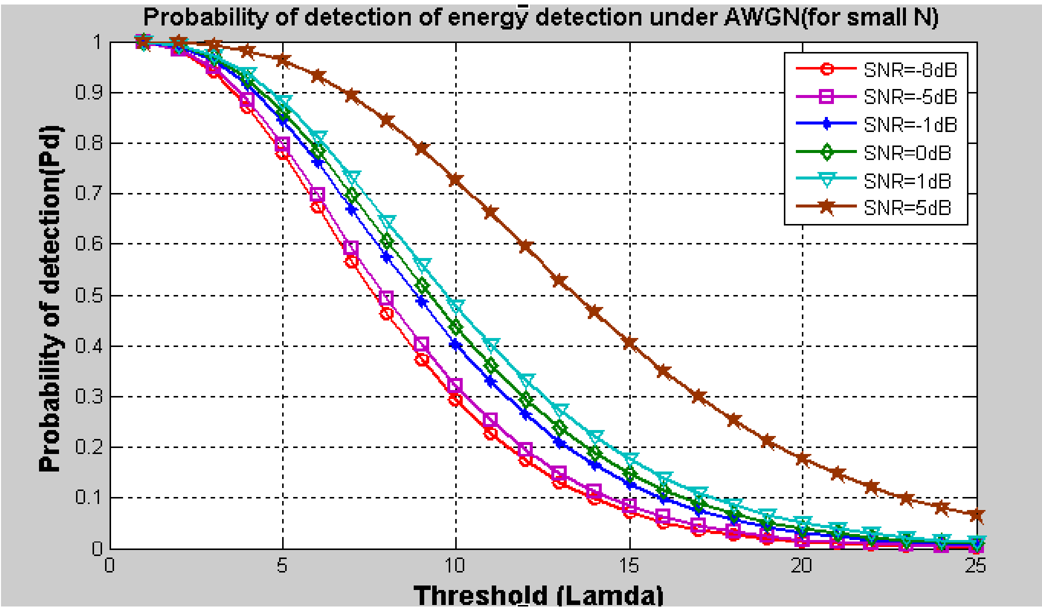

Figure 4. P_d for energy detection under AWGN for various SNR (SNR=-8dB, -5dB, -1dB, 0dB, 1dB and 5dB)

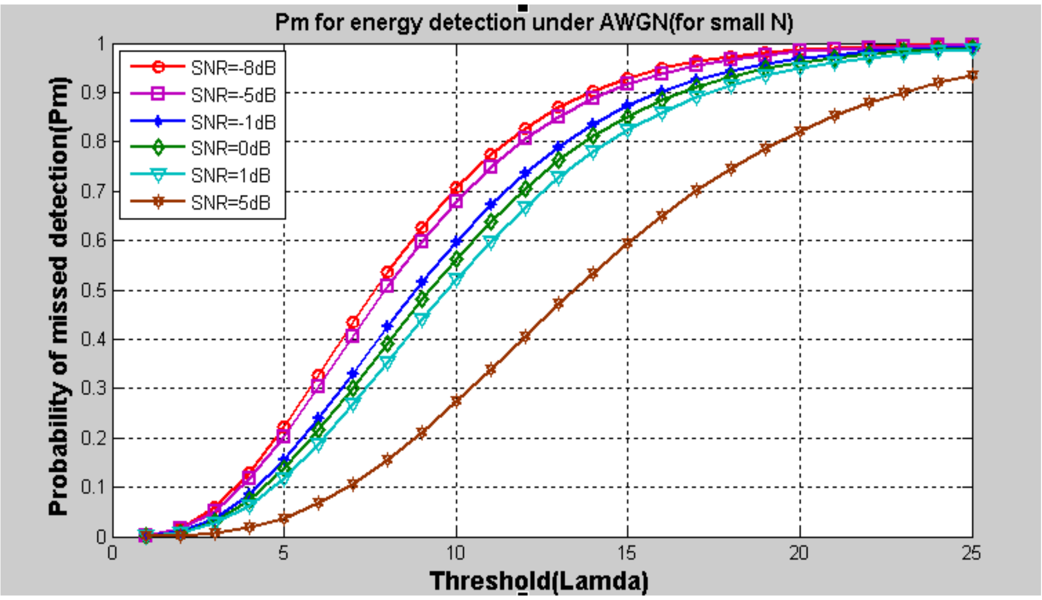

Figure 5. P_m versus threshold for energy detector under AWGN for various SNR (SNR=-8dB, -5dB, -1dB, 0dB, 1dB and 5dB)

Fig. 6 shows P_f versus sensing time plotted for various P_d values. To get better performance of detector with minimum values of P_f, the detector needs large sensing time. For example, to have $P_f = 0.1$, $P_d = 0.7$, the detector needs sensing time of 2 ms. But for $P_d = 0.9$, it needs sensing time of almost 2.3 ms.

Similarly, Fig. 7, displays P_d versus sensing time for various P_f values. Here also, to obtain better performance of higher P_d, for a fixed value of P_f, higher sensing time is required. However, longer sensing time means less time for actual transmission. This could reduce the overall throughput of the system.

Fig. 8 and Fig. 9 show, respectively, the results for the performance metrics of ROC (plot of P_d versus P_f) and CROC (plot of probability of miss detection (P_m) versus P_f) of energy detector under AWGN for various SNR values. One can observe that as the SNR increases P_d is better and P_m is minimum for a fixed P_f.

An increase in probability of detection can be achieved by increasing the number of samples. Fig 10 shows the number of samples versus SNR of energy detector for different probability of detection. It can be seen that if the SNR level of received signal is high, the detector requires smaller number of observations or samples.

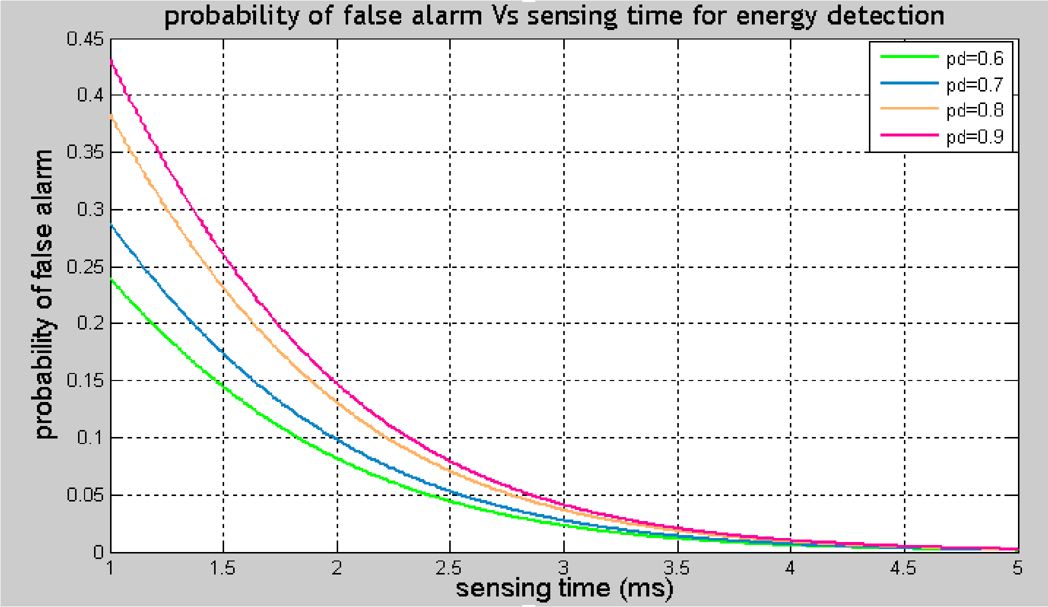

Figure 6. P_f versus sensing time for various values of Pd (SNR=-8dB)

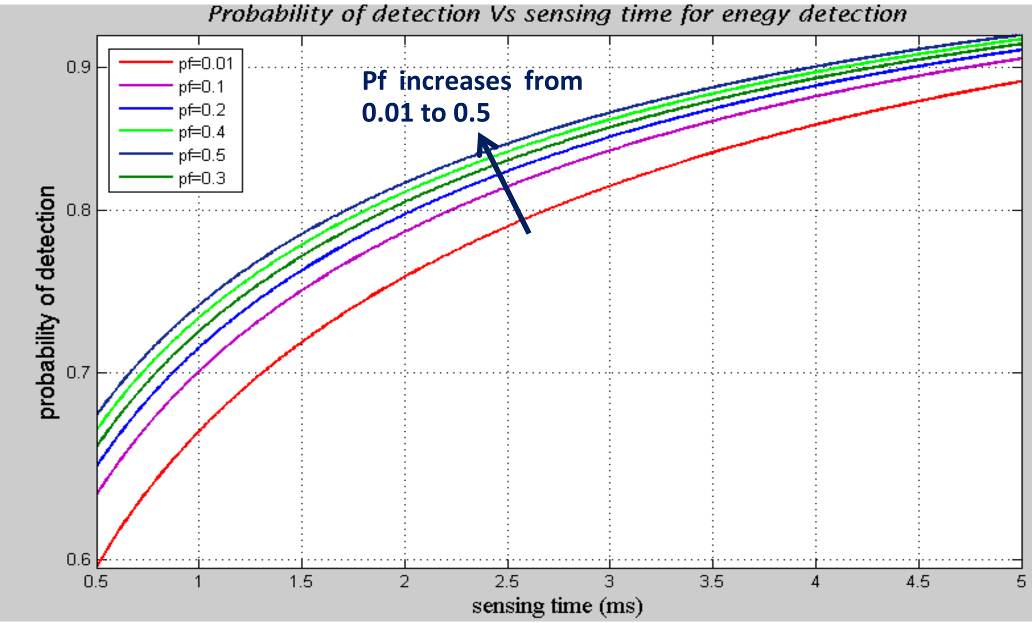

Figure 7. Probability of detection (P_d) versus sensing time for various values of Pf

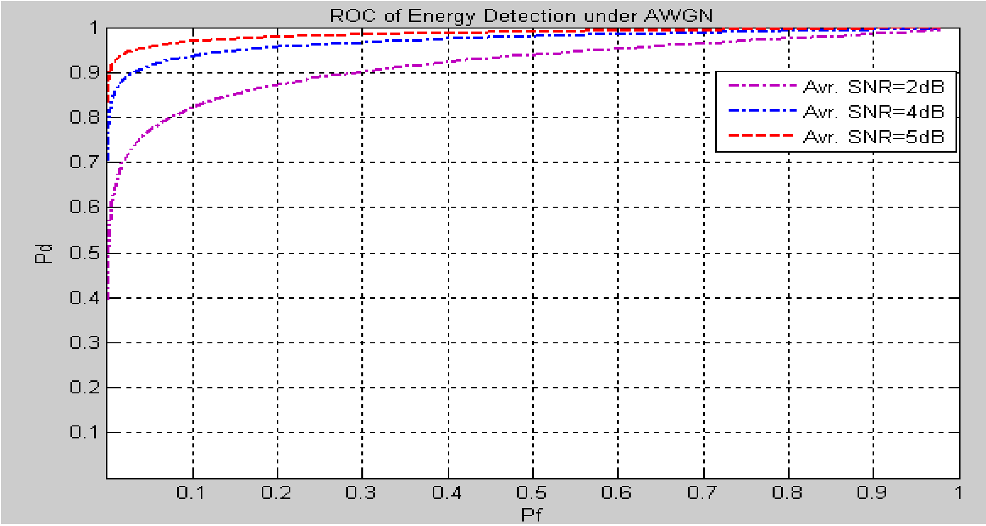

Figure 8. ROC of energy detector under AWGN for SNR of 2dB, 4dB and 5dB

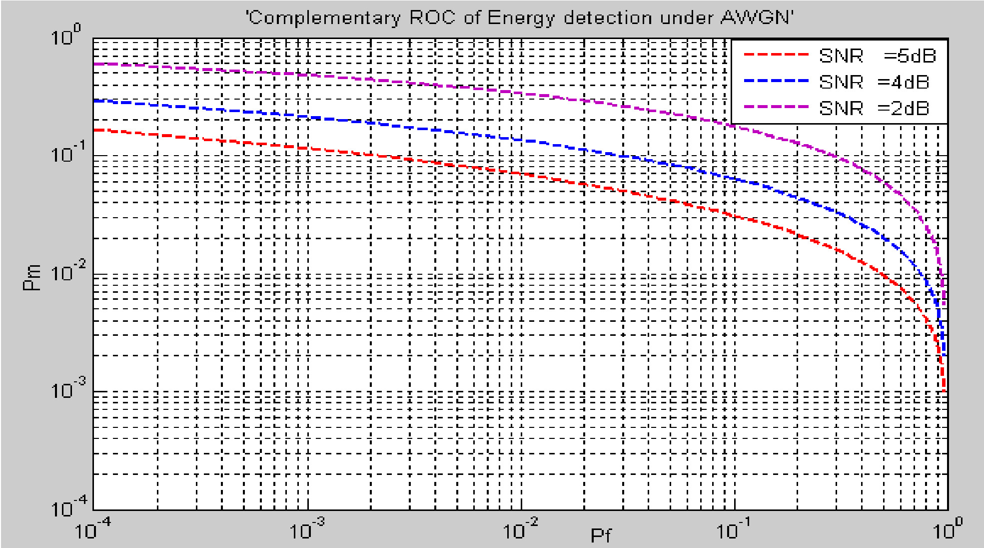

Figure 9. CROC for energy detector under AWGN for SNR of 2dB, 4dB and 5dB

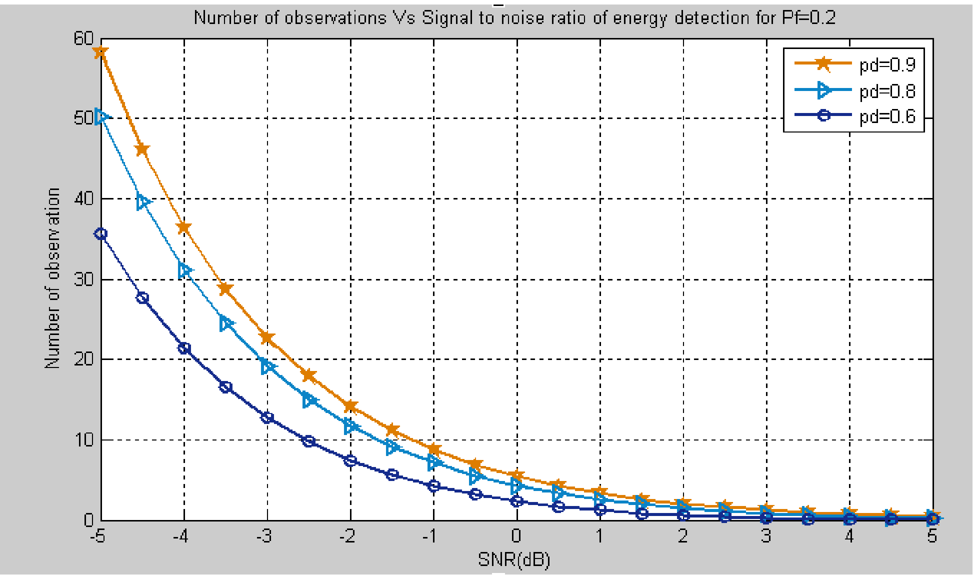

Figure 10. Number of samples versus SNR of energy detector for different probability of detection (Pd=0.6, 0.8 and 0.9)

3.2. Simulation Results for the Enhanced Energy Detector

Simulations are carried out to show the performance enhancement for the energy detector algorithm by using cross correlation of time shifted signal observations. The simulations are carried out for both AWGN and Rayleigh fading channel-using SNR of 2dB. Fig. 11 indicates probability of miss detection of energy and enhanced energy detector under AWGN for probability of false alarm of 1%.

Fig. 12 shows CROC performance of energy and enhanced energy detector under AWGN. As one can see from the results, the cross correlation based energy detector has improved the performance of energy detector. That means it is possible to get minimum probability of miss detection which results in better performance by delivering greater probability of detection.

The simulation results shown in Fig. 13 and 14 are simulated under Rayleigh fading channel. Both receiver operating characteristics (ROC) and complementary receiver operating characteristics CROC) plots clearly show that the performance of energy detector is enhanced.

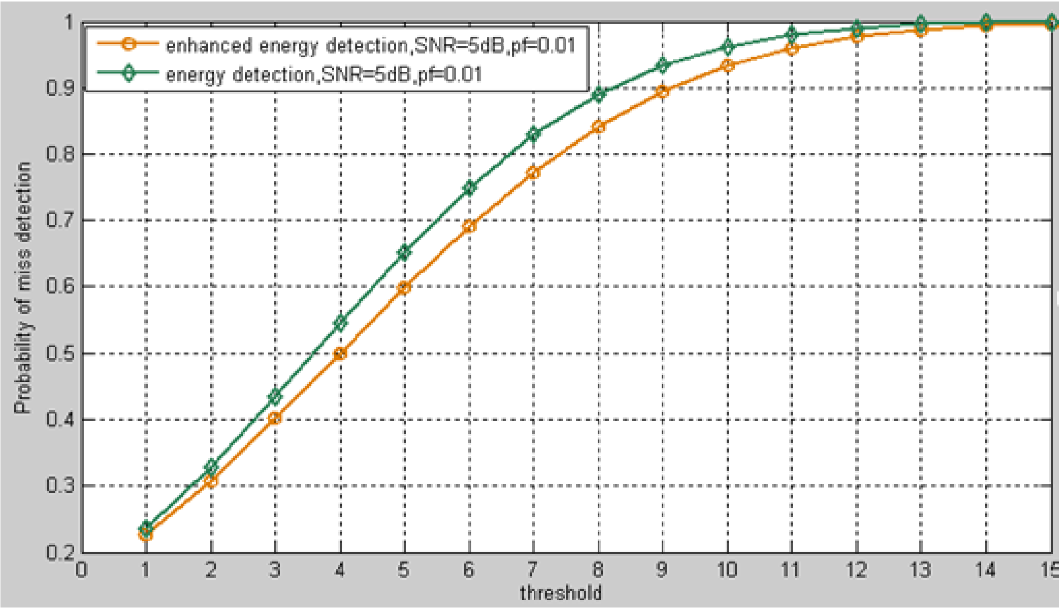

Figure 11. Probability of miss detection versus threshold for the detectors under AWGN (SNR=5dB and Pf=1%)

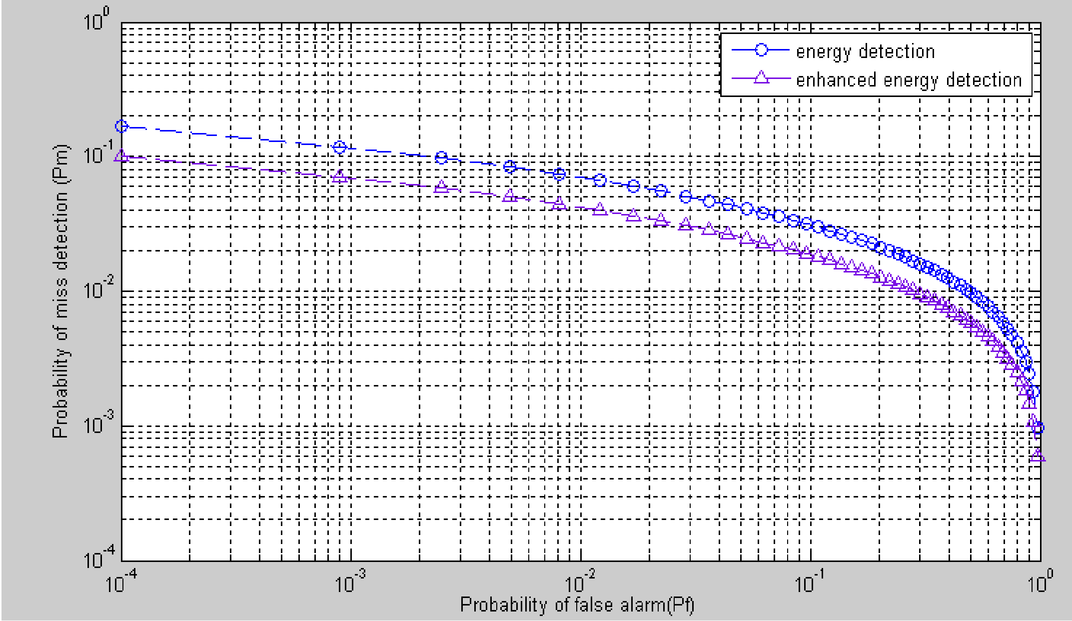

Figure 12. CROC performance of energy and enhanced energy detector Under AWGN

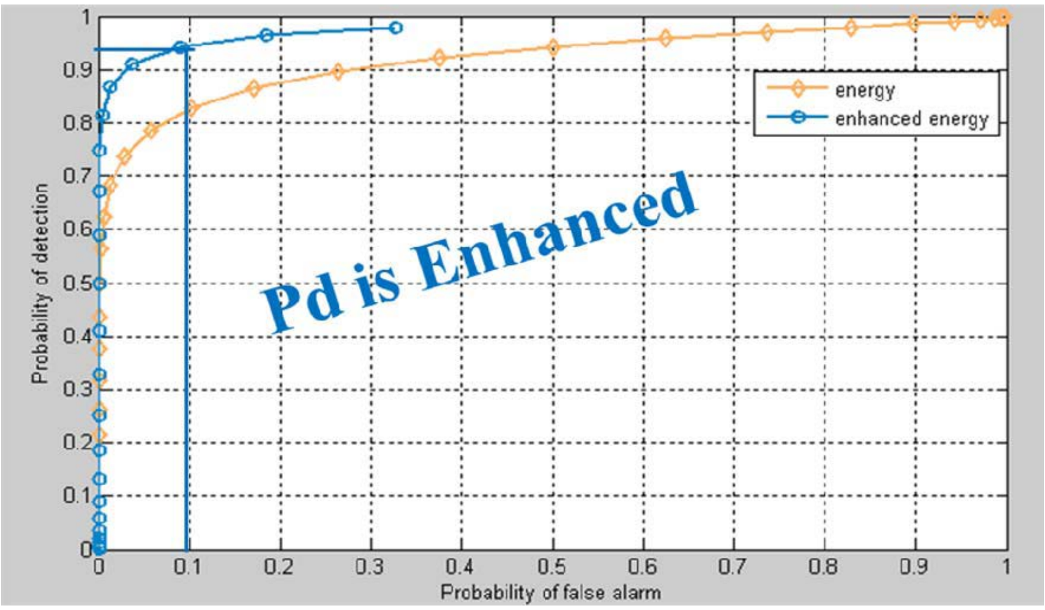

Figure 13. ROC performance of energy and enhanced energy detection Under Rayleigh fading channel

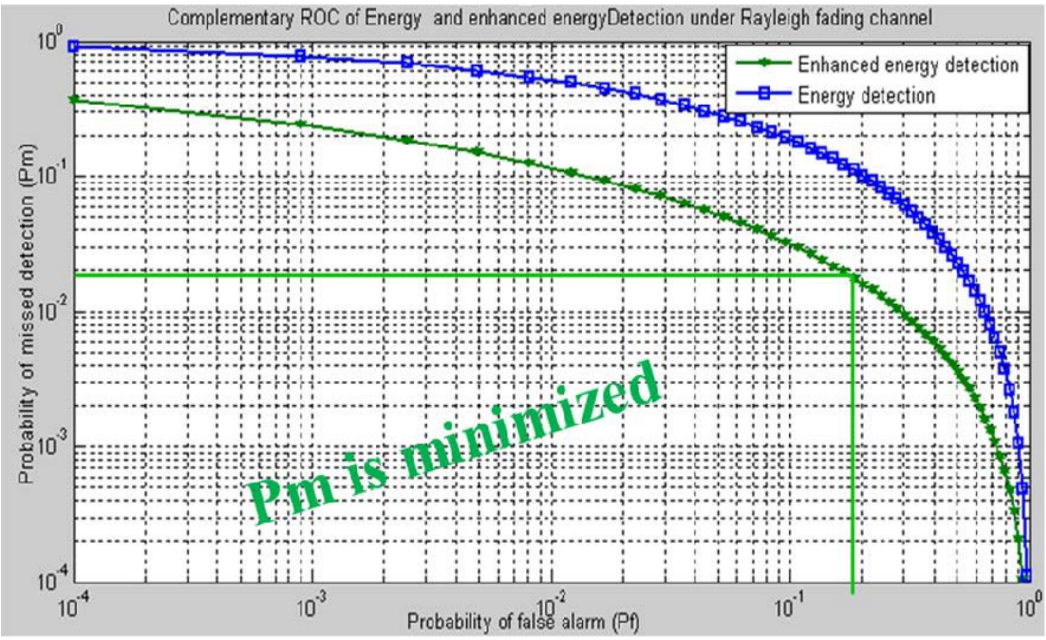

Figure 14. CROC performance of energy and enhanced energy detection Under Rayleigh fading channel

4. Conclusions

In this work performance evaluation on transmitter detector techniques has been conducted using Matlab. Effective spectrum detection and performance under AWGN and Rayleigh fading channels to minimize interference between primary and secondary users in CR systems has been discussed. Based on the simulated results the following conclusions are drawn. Energy detector drops its performance for lower SNR value and this is shown by P_d, P_m and ROC. To reduce the chance of interference with the primary users, an increase in probability of detection is needed and this is done by increasing number of samples and sensing time. The simulation results showed that in order to have $P_f = 0.1$ and $P_d = 0.7$, the detector needs sensing time of 2 ms. But for $P_d = 0.9$, it needs sensing time of almost 2.3 ms.

Finally, the performances of enhanced energy detection algorithm method are compared with the standard square law energy detection algorithm and simulation results indicate that the enhanced energy detection method has better performance than the classical energy detection algorithm. In fact the probability of detection is enhanced by as much as 0.15 when P_f is 0.1 and the probability missed detection is minimized by a factor of 5 when P_f is 0.2.

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