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# ED-SS based Cognitive Radio (CR) over Various Fading Channels for Modern Wireless Communications

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***Abstract:*** **-** Cognitive Radio (CR) has already been proved to provide the better solution for the problem of spectrum insufficiency in which every wireless system occupies the limited bandwidth spectrum (LBS) allotting to the licensed users. Sometimes, this LBS is empty in a certain place at a certain time that is called as spectrum holes estimated by spectrum sensing (SS). The spectrum sensing is the main technique used in cognitive radio and various spectrum sensing techniques are available in the literature such as: energy detection (ED), matched filter detection (MFD) and cyclo-stationary feature detection (CFD). In the present work, energy detection-spectrum sensing (ED-SS) based cognitive radio system has been implemented which can analyze the energy of the spectrum. The various fading channels such as additive white gaussian noise (AWGN), Rayleigh, and Nakagami have been incorporated in the present work over which the performance of cognitive radio has been analyzed and compared using the ED-SS technique. The experimental results show thatt the detection of the presence of primary user signal using proposed ED-SS technique is easier with low computational complexities in Cognitive Radio (CR) networks. The present work also demonstrates when the performance of proposed ED-SS technique over aforesaid three fading channels are compared, Nakagami-m fading channels exhibits superior improvement in Pd compared to Rayleigh and AWGN fading channels

***Keywords:*** Cognitive Radio (CR); Energy Detection-Spectrum Sensing (ED-SS); Fading Channels; Modern Wireless Communications

## 1. Introduction

In the present scenario, wireless services are going to be developed day by day and wideband spectrum has been employed extensively due to which spectrum scarcity has become the serious and challenging task for the researchers all around the world. This serious issue has come into the picture due to sustained growth of data rate applications. In this regard, CR- networks have been implemented to manage spectrum resources effectively and make full use of limited spectrum bands efficiently [1]. Spectrum sensing (SS) for cognitive radio (CR) networks enables cognitive users (CUs)/secondary users (SUs) to better access of allocated wideband of primary users (PUs)

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[2]. SS techniques have broadly been classified in to three categories such as: energy detection (ED), matched filter detection (MFD) and cyclo-stationary feature detection (CFD).

The MFD technique is implemented in the digital domain and requires exact bandwidth, modulation type transmission information and the minimum possible number of samples [3]. Similarly, CFD takes statistical characteristics of transmitted signals to improve the detection probability of detective model [4]. In the same continuation, one of the popular spectrum sensing (SS) techniques is ED and it is based upon non continuous synthetic dataset (NCSD) algorithm [5] and the performance analysis of ED algorithm has become an active area of research all around the world [6].

Firstly, binary hypothesis-testing signal detection over a flat band-limited Gaussian noise channel had been adopted by Urkowitz [7]. In the same direction, the ED model was considered by Kostylev and Alouini over conventional & multipath fading channels with and without diversity combining like: Rayleigh, Nakagami-q and Nakagami-m [8]. The investigations of ED for SS over different communication circumstances are available in the literature [9-10].

On the other hand, as multipath/shadowing effects affect wireless radio propagation, it was necessary to derive the adequate fading expressions [11]. In this direction, numerous fading channels/distributions are available in the literature [12-14]. Furthermore, some of special classical distributions have been developed by estimating the fading parameters α, κ and μ [15]. Further, using ED-SS, the performance of CR-system has also been analyzed and compared over various fading channels [16-17].

The Signal processing in cognitive radio has been explained in [18]. An asymptotic bound for the maximum error using the central limit theorem to approximate the distribution of chi square and noncentral chi square random variables has been derived and this has been used to calculate the decision probabilities of energy detectors [19]. A new approach based on the contour integral representation of the Marcum-Q function and the moment generating function (MGF) of the signal-to-noise ratio (SNR) has been developed to analyze the performance of the energy detector [20-22]. The performance of an energy detector over wireless channels with composite multipath fading and shadowing effects modeled by using the K and K_G channel models has been studied in [23]. The performance analysis of cognitive radio systems based on energy detection based on power spectral density estimation has been derived and using the periodogram estimate, the derivation of the probabilities of false alarm and missed detection has been given [24]. the problem of energy detection of an unknown signal over a multipath channel has been addressed [25]. The distributed spectrum sensing and access strategies for opportunistic spectrum access (OSA) under an energy constraint on secondary users has been designed [26] and the standardization and research in cognitive and dynamic spectrum access networks have been described in the work [27].

The variation in detection probability $P_d$ with variation in signal to noise ratio (SNR) and false alarm probability $P_{fa}$ has been explained in [28]. A novel spectrum sensing strategy in an energy efficient manner for selecting the most suitable target hole has been proposed [29] and a comparative study with existing spectrum sensing strategies in CR networks in a theoretical manner has also been given in [29]. To evaluate the detection performance, the area under the ROC curve (AUC) has been derived and evaluated for different multipath fading and shadowing conditions [30]. A new algorithm for sensing the spectrum occupancy with ED in n consecutive sensing time slots has been described in [31]. The distributed and cooperative spectrum sensing has been discussed in [32] including the explanation of Adapt-Then-Combine (ATC) method of diffusion technique. An adaptive double threshold cooperative spectrum sensing algorithm based on history energy detection for remedy of lower detection probability and longer spectrum sensing time has been proposed [33]. In [34], a channel state information (CSI) based multiple relay antenna selection and transmit power reduction scheme has been proposed. In this regard, fuzzy rule-based system [35-37] and swarm intelligence [38-40] have been investigated. MATLAB simulations reveal the effectiveness of the scheme in CR-networks. Rayleigh flat fading channel has been assumed in the given study.

Being motivated by the aforesaid literature regarding CR, the advantages of ED-SS over other SS techniques and various available fading channels, a CR system has been implemented using ED-SS technique. The proposed work fulfil the performance requirements for the IEEE802.22 WRAN Standards [41]

The rest of the manuscript has been organized as follow: Section 2 illustrates the basic concepts and system modelling. The related details of ED-SS based CR system is given in Section 2.1 which illustrates the basic block diagram of ED-SS system, flow chart for the process of energy detection with appropriate notations, definition and explanation of all the considered performance parameters. The details regarding considered fading channels are given in Sections 2.2 and 2.3. Section 2.2 elaborates $P_d$ and $P_{fa}$ over AWGN channel in which an AWGN channel is explained along with the supporting mathematical expressions. Section 2.3 describes $P_d$ and $P_{fa}$ over fading channels without diversity along with various supporting mathematical expressions. Section 3 demonstrates the strong experimental results in depth along with their detailed discussions. Section 3.1 gives the study about the performance of ED-SS based CR over AWGN channel, Section 3.2 provides the performance of ED-SS based CR over Rayleigh Channel and the Performance of ED-SS based CR over Nakagami fading channel is given in Section 3.3. The results have been obtained using MATLAB simulation, barchart representation and tables. The overall work is concluded in Section 4 followed by references.

## 2. Research Background (Basic Concepts and System Modelling)

There are some basic concepts related to the present work have been given below:

### *2.1. ED-SS*

It has already been found that ED has proved itself better over other techniques since it is simple, ease of signal processing, low complex and robust to variations of primary signal because there is no need of prior information of primary signal [16]. Depending on the energy of the observed signal, present or absent of primary signal is decided by treating the primary signal as noise. Mostly ED is used for wide-band spectrum sensing (WBSS) [18].

The process of Energy Detection is shown in Fig. 1(a) in which the primary signal is treated as noise by an energy detector (ED). The presence or absence of the primary signal is decided by ED depending upon the energy of the observed signal. The ED is robust to the variation of the primary signal s ince it does not need any a prior knowledge of the primary signal.

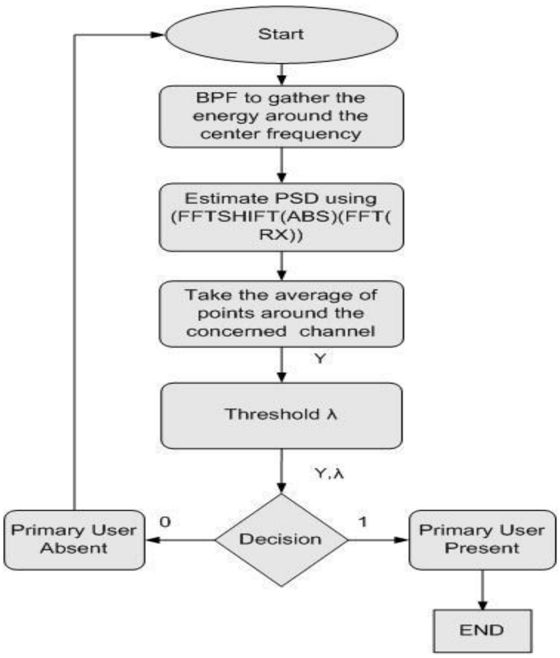


**Figure1(a).** Flowchart for the process of energy detection

The ED is mainly assigned a predefined energy threshold, λ and its value is used to measure the following three factors which appraise the performance of the detector:

The probability of false alarm, Pfa,

The probability of detection, Pd and

The probability of missed detection $P_{md}$= 1 - $P_d$

ED-SS can be understood by Fig. 1. In Fig. 1, the integrator provides the received signal energy after filtration during time duration $T$ which tests both, $H_0$ and $H_1$ [19]. Therefore, three important cases have been observed such as: Probability of Detection ($P_d$), Probability of Missed-Detection ($P_{md}$) and Probability of False Alarm ($P_{fa}$).

The received signal follows a two-hypothesis given below [20].

$$r(t) = \begin{cases} n(t) & : \quad H_0 \\ h * s(t) + n(t) & ; \quad H_1 \end{cases} \tag{1}$$

Where,

| | | |
|---|---|---|
| *r(t)* | ; | *S*ignal received by SU |
| *s(t)* | ; | *Signal transmitted by* PU |
| *n(t)* | ; | AWG-Noise |
| *h* | ; | The amplitude gain of the channel [21-22] |
| Y | ; | The output of Integrator; follows the non-central chi-square (CS) distribution [19] |
| $H_0, H_1$ | ; | The threshold detector's output |

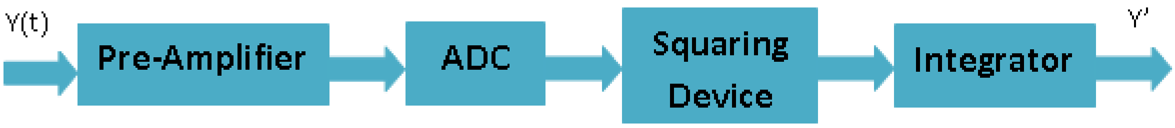


**Figure1.** Block diagram of ED-SS

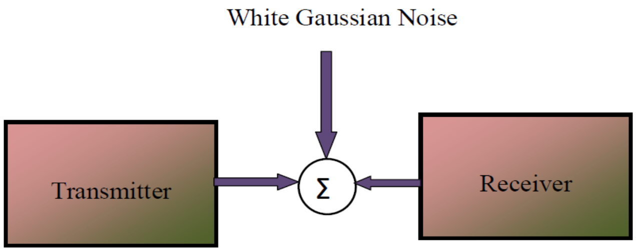


**Figure 2.** Model of AWGN Channel

The output of integrator Y is defined as:

$$Y \triangleq \frac{2}{N_0}\int_0^T r^2(t)\, d(t) \tag{2}$$

$$y \sim \begin{cases} \chi_N^2 & ; \ H_0 \\ \chi_N^2(2\gamma); & H_1 \end{cases} \tag{3}$$

where $\mu = a\gamma$. Given $H_{0,}$ $y$ will be the sample value of Y and it will be central CS distribution. For the present study, $\sigma^2 = 1$ and *a=2* have been considered which yields PDF of Y as:

$$f_Y(y) = \begin{cases} \frac{1}{\sigma^2 2^{N/2}\Gamma(N/2)} y^{N/2-1} e^{-\frac{y}{2\sigma^2}}; & H_0 \\ \frac{1}{2\sigma^2}\left(\frac{y}{a\gamma}\right)^{\frac{N-2}{4}} e^{-\frac{a\gamma+y}{2\sigma^2}} I_{N/2-1}\left(\frac{\sqrt{a\gamma y}}{\sigma^2}\right) & : \ H_1 \end{cases} \tag{4}$$

Where $\Gamma(.)$ and $I_V(.)$ are Gamma and first kind modified Bessel Function of $V^{th}$ order, respectively [19].

An energy threshold: λ is defined for energy detector whose value evaluates its performance which in turn corresponds three cases of probabilities as previously discussed called: $P_{fa}$, $P_d$ and $P_{md} = 1 - P_d$ [23]. Where,

$$P_{fa} = Pr(y > \lambda \,|H_0) \tag{5}$$

$$P_d = Pr(y > \lambda \,|\, H_1) \tag{6}$$

*2.2. $P_d$ and $P_{fa}$ over AWGN Channel*

A simplest RF environment for wireless communication system is AWGN channel (Fig. 2) in which *h=1* corresponds no fading/shadowing effect on the signal.

In this model, a White Gaussian noise having a zero mean is added to the signal as shown in Fig. 2. The noise is usually assumed to be white over the bandwidth of concern, i.e., the samples of the noise process are uncorrelated with each other. Noise has an auto-correlation function given by $\frac{N_0}{2}\delta(t)$, where $\delta(t)$ is the Dirac-delta function or, homogenously, it has a flat two-sided power spectral density. For fixed satellite communication, in which there is a direct line-of-sight path between the transmitter and satellite.

For AWGN channel, $P_d$ and $P_{fa}$ are derived by the following expressions:

$$P_{fa} = \frac{\Gamma\left( N/2 \, \frac{\lambda}{2\sigma^2} \right)}{\Gamma\left( N/2 \right)} \tag{7}$$

$$P_d = Q_{N/2}\left( \sqrt{\frac{a\gamma}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}} \right) \tag{8}$$

Where, Gamma $\Gamma(a)$ function is defined as:

$$\Gamma(t) = \int_0^\infty x^{t-1} e^{-x} dx \tag{9}$$

and generalized Marcum Q function ; $Q_{N/2}$ is given as [24]:

$$Q_M(a, b) = \int_b^\infty x \left( \frac{x}{a} \right)^{M-1} \exp\left( -\frac{x^2 + a^2}{2} \right) I_{M-1}(ax)\, dx \tag{10}$$

*2.3. $P_d$ and $P_{fa}$ over Fading Channels Without Diversity Channel*

In the present work, two kinds of fading channels have been considered for the sake of performance analysis of ED-SS based CR system such as: Nakagami-m and Rayleigh fading channels. It has been assumed that $P_{fa}$ is free from SNR which corresponds that $P_{fa}$ is same in this case as in AWGN channel. The PDF of SNR over Nakagami-m channel is defined as:

$$f_{Nak}(\gamma) = \frac{1}{\Gamma(m)} \left( \frac{m}{\bar{\gamma}} \right)^m \gamma^{m-1} exp\left( \frac{-m\gamma}{\bar{\gamma}} \right), \gamma = 0 \tag{11}$$

Where,

$m$ ; Nakagami parameter and

$\bar{\gamma}$ ; Average SNR.

The average $P_d$ denoted as $\overline{P_d}Nak$ for a Nakagami-m channel is given as [25] :

$$\overline{P_d}Nak = A_1 + \beta^m e^{\frac{-\lambda}{2\sigma^2}} * \sum_{i=1}^{N/2-1} \frac{\left( \frac{\lambda}{2\sigma^2} \right)^i}{i!} F_1\left( m; i+1; \frac{\lambda(1-\beta)}{2\sigma^2} \right) \tag{12}$$

Where $\beta = \frac{(2m\sigma^2)}{(2m\sigma^2 + a\bar{\gamma})} F_{1\,(m;i)}$ is a confluent hyper geometric function [25], and for integer m, $A_1$ has been defined as:

$$A_1 = e^{\frac{-\lambda\,\beta}{2m\sigma^2}}\left[\beta^{m-1}L_{m-1}\left(\frac{-\lambda\,(1-\beta)}{2\sigma^2}\right)+(1-\beta)\sum_{i=0}^{m-2}L_i\left(\frac{-\lambda\,(1-\beta)}{2\sigma^2}\right)\right] \tag{13}$$

Where $L_i(.)$ is called as the lagurre polynomial of degree *i*.

The average $P_d$ over Rayleigh fading channel $\bar{P}_d\ Ray$ may be obtained using by-product of the above result (taking $m = 1$ in (10 & 11)). It is given as:

$$\overline{P_d}Ray = e^{-\lambda/2\sigma^2}\sum_{i=0}^{N/2-1}\frac{\left(\frac{\lambda}{2\sigma^2}\right)^i}{i!}+\left(\frac{2\sigma^2+a\bar{\gamma}}{a\bar{\gamma}}\right)^{N/2-1} * \left[e^{\frac{-\lambda}{2\sigma^2+a\bar{\gamma}}}-e^{-\lambda/2\sigma^2}\sum_{i=0}^{\frac{N}{2}-1}\frac{\left(\frac{\lambda a\bar{\gamma}}{2\sigma^2(2\sigma^2+a\bar{\gamma})}\right)^i}{i!}\right] \tag{14}$$

**3. Results and Discussions**

The performance of SS techniques has been examined by the $P_d$, $P_{fa}$, $P_{md} = 1-P_d$ and ROC [26]. MATLAB of version 7.10.0 (R2010a) has been used to perform simulation work for three different fading channels considered above. The performance of receiver has been described by ROC curves for different values of $P_{fa}$, $P_d$ and SNR [27].

*3.1. Performance of ED-SS based CR over AWGN Channel*

Here, the performance of ED-SS based CR over AWGN channel is evaluated on the basis of the behavior of the $P_d$ along with the variation in SNR (dB) at different values of $P_{fa}$.. In the present work, two cases of time bandwidth factor *N* (*N*=1000 and *N*=5000) have been considered for the sake of analysis of ED-SS based CR system using ROC.

The receiver operating characteristic (ROC) curve is basically a plot of test sensitivity as the y coordinate versus its 1-specificity or false positive rate (FPR) as the x coordinate. This is and effective method of evaluating the quality or performance of the scheme presented here (ED-SS}. The ROC analysis is a prerequisite for the correct use and interpretation of the results that it provides.

*3.1.1. Case-I: N=1000*

For this purpose, N=1000 is considered for obtaining the performance of ED-SS based CR system. The simulation results of variation in $P_d$ with SNR for $P_{fa}$=*0.01*, *0.05* and *0.1* have been given in Table-II which depicts the following observations:

**Table 1.** Variation of $P_d$ with Variation in $P_{fa}$ in ED-SS based CR for AWGN Channel

| SNR (dB) | $P_d$ at $P_{fa}$=0.01 | $P_d$ at $P_{fa}$ = 0.05 | $P_d$ at $P_{fa}$=0.1 | % Imp. (10% increase in $P_{fa}$) |
|---|---|---|---|---|
| **-20** | 0.0795 | 0.1762 | 0.2495 | 68.13 |
| **-19** | 0.0890 | 0.1921 | 0.2685 | 66.85 |
| **-18** | 0.1021 | 0.2131 | 0.2937 | 65.23 |

| | | | | |
|---|---|---|---|---|
| **-17** | 0.1198 | 0.2412 | 0.3261 | 63.26 |
| **-16** | 0.1454 | 0.2788 | 0.3685 | 60.54 |
| **-15** | 0.1817 | 0.3291 | 0.4235 | 57.09 |
| **-14** | 0.2341 | 0.3966 | 0.4936 | 52.57 |
| **-13** | 0.3089 | 0.4838 | 0.5808 | 46.81 |
| **-12** | 0.4128 | 0.5921 | 0.682 | 39.47 |
| **-11** | 0.5484 | 0.7151 | 0.7898 | 30.56 |
| **-10** | 0.7044 | 0.8354 | 0.8868 | 20.58 |
| **-9** | 0.8506 | 0.9287 | 0.9550 | 10.98 |
| **-8** | 0.9496 | 0.9802 | 0.9888 | 3.92 |
| **-7** | 0.9907 | 0.9971 | 0.9986 | 0.8 |
| **-6** | 0.9991 | 0.9999 | 0.9999 | 0 |
| **-5** | 1 | 1 | 1 | 0 |
| **-4** | 1 | 1 | 1 | 0 |
| **-3** | 1 | 1 | 1 | 0 |
| **-2** | 1 | 1 | 1 | 0 |
| **-1** | 1 | 1 | 1 | 0 |
| **0** | 1 | 1 | 1 | 0 |

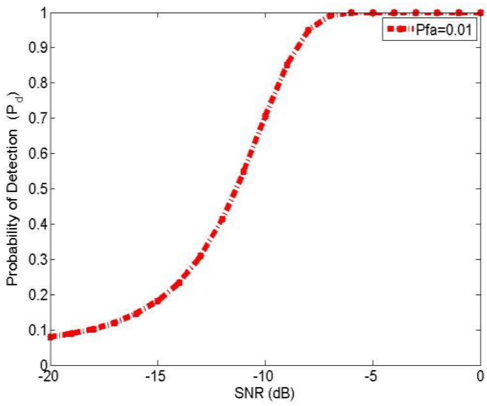


**Figure 3.** ROC for the variation in $P_d$ with variation in SNR at $P_{fa}$ =0.01 and *N*=1000

For the same value of $P_{fa}$, the $P_d$ increases with increase in SNR (dB). After SNR=-5dB, the $P_d$ becomes unity and there is no change with change in SNR for constant $P_{fa}$. The $P_d$ will increase with increase in $P_{fa}$ at constant SNR over AWGN channel and percentage improvement in $P_d$ with 10% increase in $P_{fa}$ (from 0.01 to 0.1) at constant SNR has also been shown in table I. The variation of % improvement (for 10% increase in $P_{fa}$) with the variation of SNR has been shown in Fig.7. The results of ROC can be seen in Figs. 3-5 for $P_{fa}$=*0.01*, *0.05* and *0.1* and the overall comparison curve has also been shown in Fig. 6.

*3.1.2. Case-II: N=5000*

In case II, $N$=5000 has been considered for obtaining the performance of ED-SS based CR system. Table-III shows the simulation results of fluctuation in Pd with SNR for Pfa=0.01, 0.05, and 0.1, with the following results:

For the same value of $P_{fa}$, the $P_d$ increases with increase in SNR (dB) as in Case-I. After SNR=-11dB, the $P_d$ becomes unity and there is no change with change in SNR for constant $P_{fa}$.

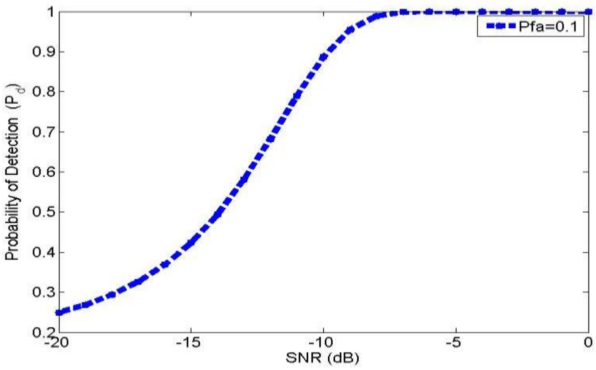


**Figure 4.** ROC for the Variation in $P_d$ with Variation in SNR at $P_{fa}$ =0.05 and $N$=1000

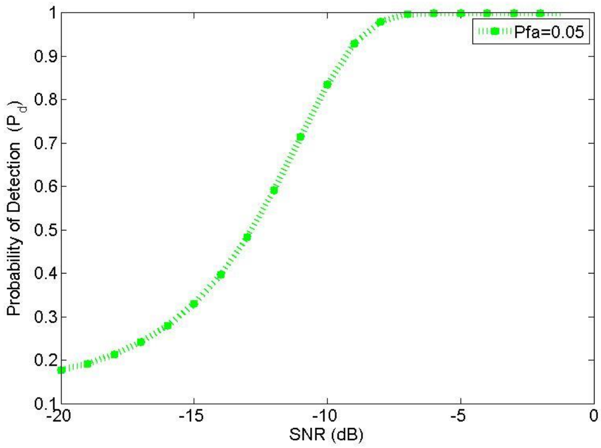


**Figure 5**. ROC for the variation in $P_d$ with Variation in SNR at $P_{fa}$ =0.1 and $N$=1000

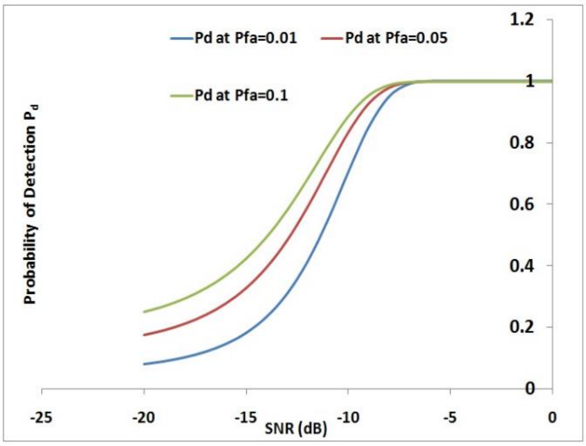

**Figure 6.** Comparative ROC for the Variation in $P_d$ with Variation in SNR at *N*=1000

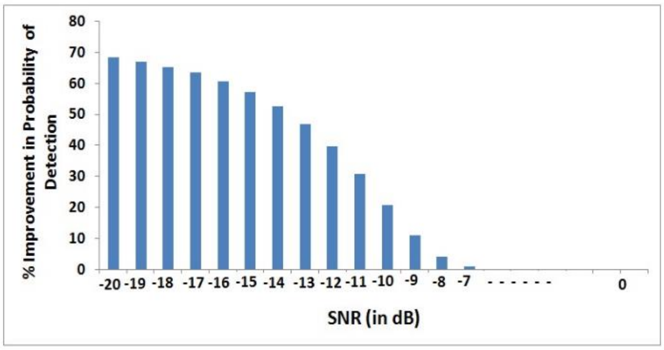


**Figure 7.** The variation of % improvement (for 10% increase in $P_{fa}$) with the variation of SNR (N=5000)

The $P_d$ will increase with increase in $P_{fa}$ at constant SNR over AWGN channel and percentage improvement in $P_d$ with 10% increase in $P_{fa}$ (from 0.01 to 0.1) at constant SNR has also been shown in Table-III. The variation of % improvement (for 10% increase in $P_{fa}$) with the variation of SNR has been shown in Fig.12. The results of ROC can be seen in Figs. 8-10 for $P_{fa}=0.01$, *0.05* and *0.1* and the overall comparison has also been shown in Fig. 11. From Table-1 and Table-II, a comparison for $N=1000$ and $N=5000$ over AWGN channel can be given as follows: It is clear that if the number of samples are increased, $P_d$ will increase with increase in $P_{fa}$ for the same SNR which yields the better performance of ED-SS based CR system for more number of samples. $P_d$ reaches to unity very fast for more number of samples as compared to less number of samples with SNR . For example, $P_d =1$ for SNR=-9 dB for $N=5000$ and $P_d =1$ for SNR=-5 dB for $N=1000$ i.e. $P_d$ reaches to 1 very fast with SNR for more number of samples as compared to less number of sample. The variation of % Improvement in $P_d$ for $N=1000$ and $N=5000$ with the variation in SNR for 10 % increase in $P_{fa}$ ($P_{fa}=0.01$ *to 0.1*) has been shown in Fig. 13.

**Table 2.** Variation of $P_D$ with variation in SNR at different $P_{FA}$ in ED-SS based CR for AWGN channel (N=5000)

| SNR (dB) | $P_d$ at $P_{fa}$=0.01 | $P_d$ at $P_{fa}$ =0.05 | $P_d$ at $P_{fa}$=0.1 | % Imp. (10% increase in $P_{fa}$) |
|---|---|---|---|---|
| **-20** | 0.1286 | 0.2556 | 0.3439 | 62.60 |
| **-19** | 0.1581 | 0.2992 | 0.3924 | 59.70 |
| **-18** | 0.2006 | 0.3575 | 0.4555 | 55.96 |
| **-17** | 0.2626 | 0.4357 | 0.5356 | 50.97 |
| **-16** | 0.3524 | 0.5362 | 0.6334 | 44.36 |
| **-15** | 0.4754 | 0.6574 | 0.7436 | 36.06 |
| **-14** | 0.6301 | 0.7868 | 0.8516 | 26.00 |
| **-13** | 0.7939 | 0.8995 | 0.9362 | 15.19 |

| | | | | |
|---|---|---|---|---|
| **-12** | 0.9221 | 0.9696 | 0.9829 | 6.18 |
| **-11** | 0.9846 | 0.9956 | 0.9979 | 1.33 |
| **-10** | 0.9989 | 0.9998 | 0.9999 | 0.1 |
| **-9** | 1 | 1 | 1 | 0 |
| **-8** | 1 | 1 | 1 | 0 |
| **-7** | 1 | 1 | 1 | 0 |
| **-6** | 1 | 1 | 1 | 0 |
| **-5** | 1 | 1 | 1 | 0 |
| **-4** | 1 | 1 | 1 | 0 |
| **-3** | 1 | 1 | 1 | 0 |
| **-2** | 1 | 1 | 1 | 0 |
| **-1** | 1 | 1 | 1 | 0 |
| **-0** | 1 | 1 | 1 | 0 |

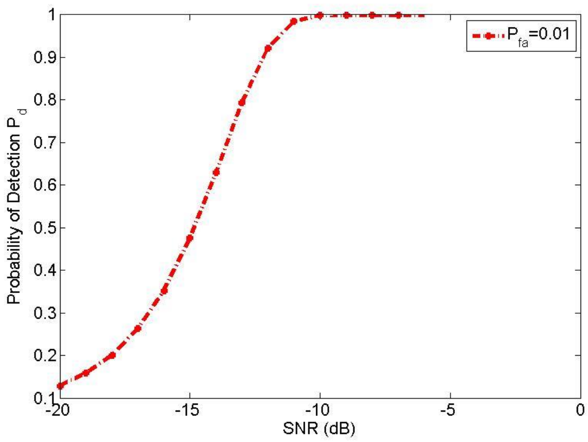


**Figure 8.** ROC for the variation in $P_d$ with variation in SNR at $P_{fa}$ =0.01 and *N*=5000

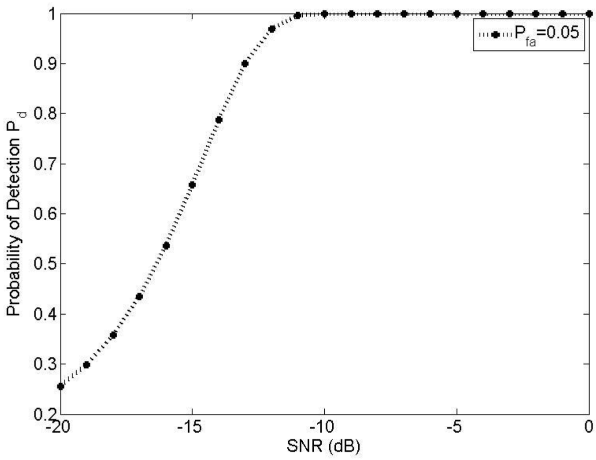


**Figure 9.** ROC for the variation in $P_d$ with variation in SNR at $P_{fa}$ =0.05 and *N*=5000

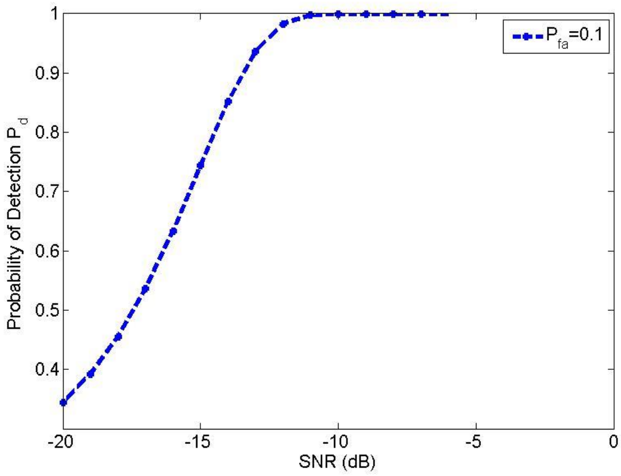


**Figure 10**. ROC for the variation in $P_d$ with variation in SNR at $P_{fa}$ =0.1 and $N$=5000

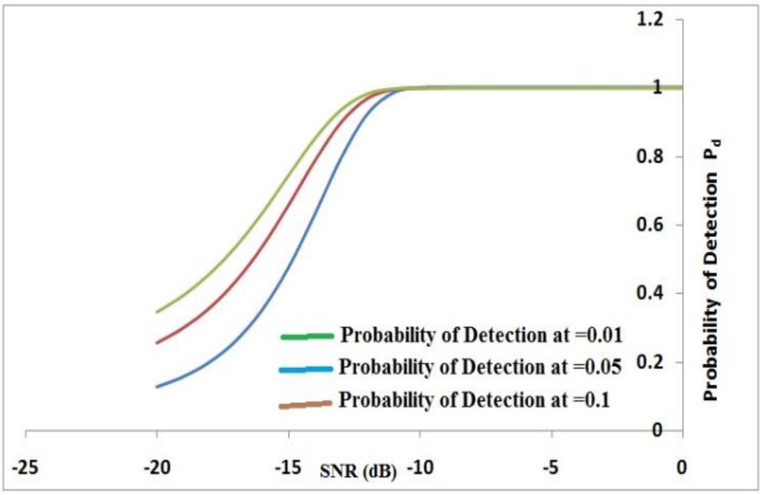


**Figure 11.** Comparative ROC for the variation in $P_d$ with variation in SNR at $N$=5000

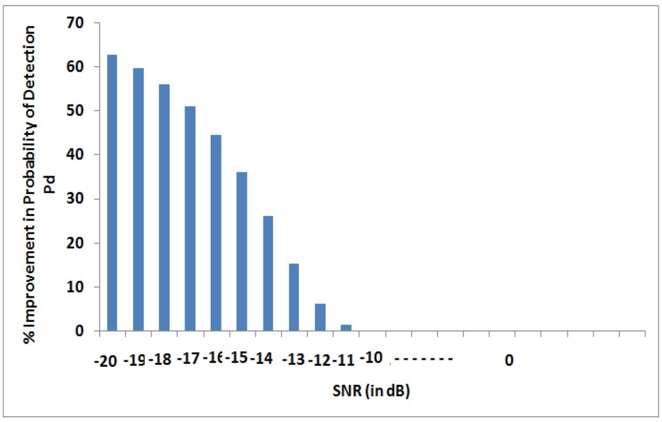

**Figure 12.** The variation of % improvement (for 10% increase in $P_{fa}$ with the variation of SNR (N=5000)

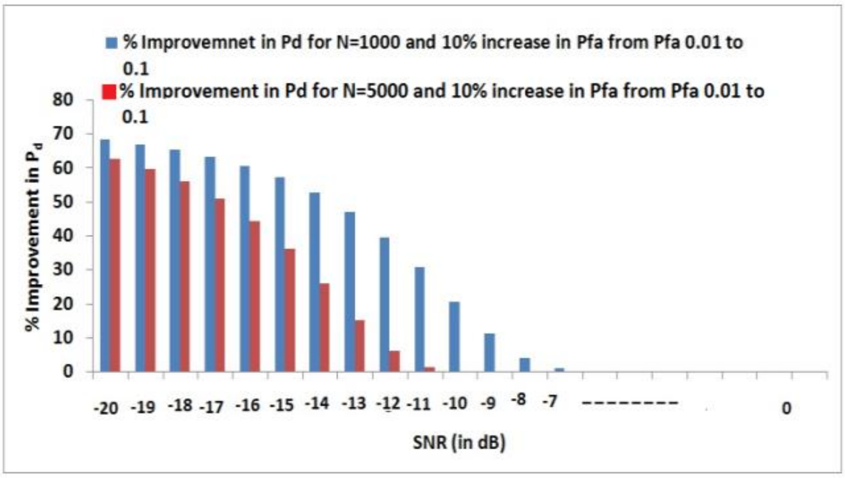


**Figure 13.** Variation of % Improvement in $P_d$ for $N=1000$ and $N=5000$ with the variation in SNR for 10 % increase in $P_{fa}$ ($P_{fa}=0.01$ *to* $0.1$)

### *3.2. Performance of ED-SS based CR over Rayleigh Channel*

The ROC of ED-SS based CR system over Rayleigh fading channel can be seen in Fig. 14 and Table 4. Fig. 14 shows the variation of $P_d$ with the variation in $P_{md}$ at different SNR over Rayleigh fading channel. From Fig. 14 and Table-IV, it has been found that For a fixed value of $P_{fa}$, $P_d$ will increase with increase in SNR, i.e. detector's performance increases with increase in SNR, For *SNR=0 dB, 5 dB* and *10 dB*, the $P_d$ reaches up to 1 when the value of $P_{md}$ is also 1 while for *SNR =15* dB, the $P_d$ up 1 at $P_{md}=0.0891$. The % improvement in $P_d$ with the variation of $P_{fa}$ for 15% increase in SNR (0 dB to 15 dB) has also been shown in Fig. 15.

### *3.3. Performance of ED-SS based CR over Nakagami Fading Channel*

The ROC of ED-SS based CR system over Nakagami-m fading channel can be seen in Fig. 16 in which the variation in $P_{md}$ has been shown with the variation in $P_{fa}$ at SNR=15 dB for different values of Nakagami Factor m (m=1-4). From Fig. 16, it has been observed that $P_{md}$ decreases as *m* increases, i.e. the performance of ED-SS based CR system increases when m increases.

**Table 3.** Variation of $P_D$ with variation in $P_{FA}$ in ED-SS based CR at different SNR over Rayleigh fading channel

| $P_{fa}$ | $P_d$ at SNR = 0dB | $P_d$ at SNR= dB | $P_d$ at SNR = 10dB | $P_d$ at SNR= 15dB | % Imp. |
|---|---|---|---|---|---|
| **0.0001** | 0.0004 | 0.0042 | 0.1317 | 0.9757 | 99.95 |
| **0.0002** | 0.0007 | 0.0062 | 0.1627 | 0.9822 | 99.92 |
| **0.0004** | 0.0015 | 0.0098 | 0.2075 | 0.9881 | 99.84 |
| **0.0007** | 0.0026 | 0.0158 | 0.2616 | 0.9924 | 99.73 |

| | | | | | |
|---|---|---|---|---|---|
| **0.0014** | 0.0045 | 0.0255 | 0.3256 | 0.9956 | 99.54 |
| **0.0016** | 0.0051 | 0.0274 | 0.3372 | 0.9958 | 99.48 |
| **0.0028** | 0.0084 | 0.0404 | 0.3994 | 0.9976 | 99.15 |
| **0.0056** | 0.0151 | 0.0634 | 0.4824 | 0.9988 | 98.48 |
| **0.0063** | 0.0167 | 0.0683 | 0.4968 | 0.9989 | 98.43 |
| **0.0112** | 0.0271 | 0.0984 | 0.5727 | 0.9993 | 97.28 |
| **0.0224** | 0.0488 | 0.1513 | 0.6669 | 0.9996 | 95.11 |
| **0.0251** | 0.0538 | 0.1625 | 0.6827 | 0.9997 | 94.61 |
| **0.0447** | 0.0876 | 0.2293 | 0.7604 | 0.9998 | 91.23 |
| **0.0891** | 0.1555 | 0.3408 | 0.8468 | 1 | 84.45 |
| **0.1000** | 0.1708 | 0.3633 | 0.8600 | 1 | 82.92 |
| **0.1778** | 0.2734 | 0.4943 | 0.9191 | 1 | 72.66 |
| **0.3548** | 0.4734 | 0.6918 | 0.9705 | 1 | 52.66 |
| **0.3981** | 0.5177 | 0.7285 | 0.9767 | 1 | 51.76 |
| **1.000** | 1 | 1.00 | 1 | 1 | 0 |

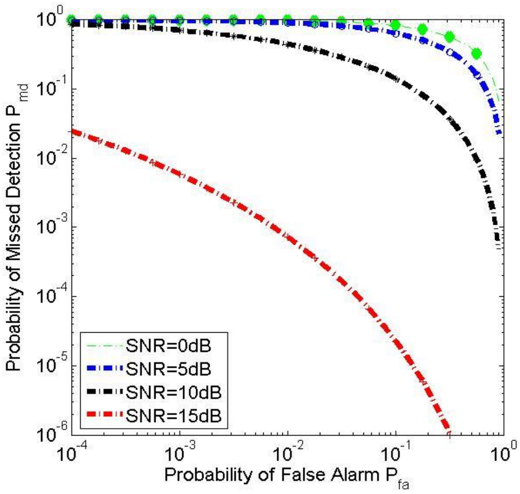


**Figure 14.** ROC for the variation in $P_d$ with variation in $P_{fa}$ at different SNR

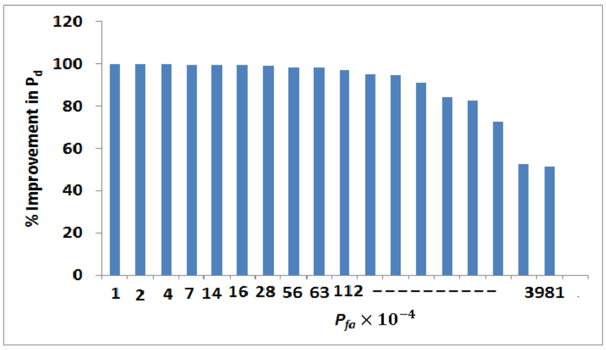

**Figure 15.** Variation of % improvement in $P_d$ with $P_{fa}$ for 15% increase in SNR

If the ROC of ED-SS over Nakagami fading channel is compared with the ROC for Rayleigh fading channel at SNR=15 dB, more decrease in $P_d$ over Nakagami fading channel is found which reveals that ED-SS based CR system delivers the better performance over Nakagami fading channel as compared to Rayleigh fading channel. Table V shows variation of $P_d$ with variation in $P_{fa}$ in ED-SS based CR system at different values of $m$ over Nakagami fading channel.

Table 4 shows that if $m$ increases from 1 to 3, the $P_d$ will also increase and the % improvement in $P_d$ has also been shown in Table 4 and Fig. 17.

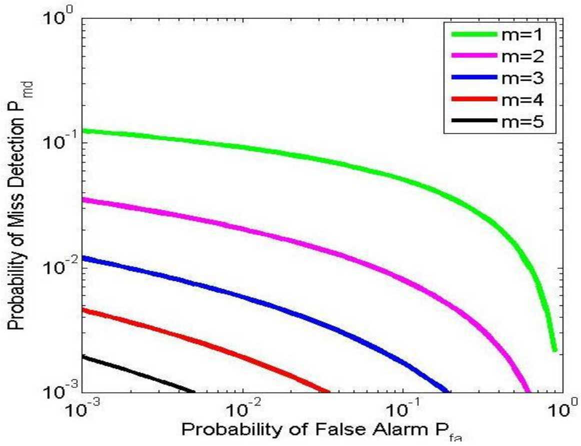


**Figure 16**. ROC for the Variation in $P_{md}$ with Variation in $P_{fa}$ at different values of *m for Nakagami fading channel*

**Table 4.** Variation of $P_D$ with variation in $P_{FA}$ in ED-SS based CR at different values of M, over Nakagami Fading Channel

| $P_{fa}$ | $P_d$ For m=1 | $P_d$ for m=2 | $P_d$ For m=3 | % Imp. |
|---|---|---|---|---|
| **0.0001** | 0.8439 | 0.9490 | 0.9801 | 13.89 |
| **0.0002** | 0.8511 | 0.9531 | 0.9823 | 13.35 |
| **0.0004** | 0.8600 | 0.9579 | 0.9847 | 12.66 |
| **0.0007** | 0.8692 | 0.9627 | 0.9870 | 11.93 |
| **0.0014** | 0.8787 | 0.9673 | 0.9891 | 11.16 |
| **0.0016** | 0.8803 | 0.9680 | 0.9895 | 11.03 |
| **0.0028** | 0.8886 | 0.9717 | 0.9911 | 10.34 |
| **0.0056** | 0.8990 | 0.9761 | 0.9929 | 9.45 |
| **0.0063** | 0.9008 | 0.9768 | 0.9931 | 9.29 |
| **0.0112** | 0.9099 | 0.9802 | 0.9945 | 8.50 |
| **0.0224** | 0.9214 | 0.9842 | 0.9959 | 7.48 |
| **0.0251** | 0.9234 | 0.9848 | 0.9961 | 7.29 |

| | | | | |
|---|---|---|---|---|
| **0.0447** | 0.9336 | 0.9879 | 0.9971 | 6.37 |
| **0.0891** | 0.9468 | 0.9914 | 0.9981 | 5.14 |
| **0.1000** | 0.9491 | 0.9920 | 0.9983 | 4.93 |
| **0.1778** | 0.9611 | 0.9946 | 0.9989 | 3.78 |
| **0.3548** | 0.9766 | 0.9973 | 0.9995 | 2.29 |
| **0.3981** | 0.9793 | 0.9977 | 0.9996 | 2.03 |
| **1.000** | 1.000 | 1 | 1 | 0 |

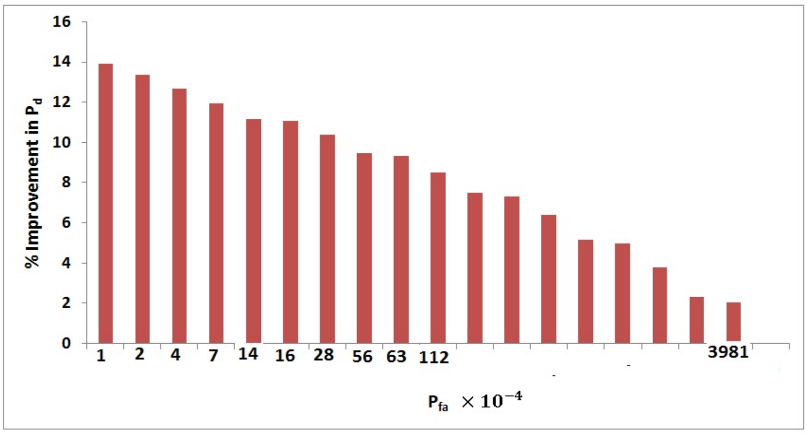


**Figure 17.** Variation of % improvement in $P_d$ with $P_{fa}$ for m=1 to 3

## 4. Conclusion

In the present work, energy detection-spectrum sensing (ED-SS) based cognitive radio system has been implemented. The energy of the spectrum and the performance of the considered ED-SS technique have been analyzed and compared over three fading channels: AWGN, Rayleigh and Nakagami-*m* fading channels. The performance of ED-SS technique over the mentioned fading channels has been examined by ROC in which the performance parameters: $P_d$, $P_{fa}$, and $P_{md} = 1\text{-}P_d$ are considered. In the study of performance of ED-SS based CR over AWGN channel, the variation in $P_d$ along with the variation in SNR (dB) at different values of $P_{fa}$ for two cases of time bandwidth factor *N* (*N*=1000 and *N*=5000) has been studied. In the performance of ED-SS based CR system over Rayleigh fading channel, the variation of $P_d$ with the variation in $P_{md}$ at different SNR has been studied and in the performance of ED-SS based CR system over Nakagami-m fading channel, the variation in $P_{md}$ with the variation in $P_{fa}$ at SNR=15 dB for different values of Nakagami Factor m (m=1-4) has been studied. The % improvement in $P_d$ for different aforesaid parameters have also been shown using bar chart representation. The above performance study shows that the detection of the presence of primary user signal using proposed ED-SS technique is easier with low computational complexities in Cognitive Radio (CR) networks. The present work also demonstrates when the performance of proposed ED-SS technique over aforesaid three fading channels are compared, Nakagami-m fading channels exhibits superior improvement in $P_d$ compared to Rayleigh and AWGN fading channels

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