Performance Evaluation of Spectrum Sensing in Cognitive Radios for Different Channel Conditions

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ABSTRACT

In this paper the detection performance of relay based cognitive radio networks is studied. Relays are assigned in cognitive radio networks to transmit the primary user's signal to cognitive coordinator or CPU thus achieving cooperative spectrum sensing. The soft fusion rule is used at the relays which acts as amplify and forward relays. For the detection purpose the energy detector is employed at the cognitive coordinator. Sensing performance is analyzed for different fading channels and comparison between different relay conditions is also studied.

Keywords

Amplify and forward, energy detector, Nakagami-m, Nakagami-n, Rayleigh, soft fusion.

1. INTRODUCTION

We know that the radio spectrum is an expensive and limited resource in wireless communication systems. Most of its usable or beneficial part has been allocated to different services or has already been licensed by the government agencies in respective countries. Therefore there exists an apparent spectrum scarcity for new wireless services. It has also been noticed that licensed users rarely utilize all the allocated frequency bands at all the time and at different geographical locations. So the underutilization of allotted frequency bands occurs and spectrum usage becomes inefficient. Such spectrum underutilization has motivated cognitive radio technology which has built in radio environment awareness and spectrum intelligence [1], [2]. Spectrum utilization can be improved significantly by allowing a secondary user to utilize a licensed band when the primary user is absent.

Cognitive radio enables opportunistic access to unused licensed bands. Unlicensed users first sense the primary users' activities and then accordingly access the spectrum holes if detected. Spectrum holes are the unused frequency bands allocated to primary user at any point of time. Therefore spectrum sensing is one of the main tasks of the cognitive radios. In spectrum sensing the accuracy is very much desirable to avoid the interference which can be caused by the secondary user's signal to the primary user's signal at the time of false alarm. It is also necessary to increase the spectrum efficiency by reducing the chances of wrong detection. But it is very hard to achieve such accuracy. The factors behind this are Multipath fading, Noise and hidden terminal problem [4]. Cooperative sensing has therefore been introduced for quick and reliable detection [6], [7], [8].

Among detection techniques such as matched filter detection and the cyclostationary feature detection [4],[5], energy detection is the most popular method [9]. Measuring only the received signal power, the energy detector is a non-coherent detection device with very low implementation complexity as it does not need any prior information about the primary user's signal. Such features make the energy detector the most commonly used detector in spectrum sensing and signal detection systems.

2. COGNITIVE RADIO

The term cognitive radio was first coined by Joseph Mitola. From his description we can define the cognitive radio as [1] "a radio capable of analyzing the environment, learning and predicting the most suitable and efficient way of using the available spectrum and adapting all of its operational parameters". Joseph Mitola is also known as the father of cognitive radios. According to Simon Haykin cognitive radio is defined as [2] "an intelligent wireless communication system that is aware of its environment, and uses the understanding by building methodology to learn from the environment and adapt to statistical variations in the input stimuli."

The Federal Communications Commission (FCC), where regulations focus on the operation of transmitters, defines a cognitive radio as [3] "a radio that can change its transmitter parameters based on the interaction with the environment in which it operates." So cognitive radio is an exciting emerging technology that has the potential of dealing with the stringent requirement and scarcity of the radio spectrum.

3. COOPERATIVE SPECTRUM SENSING

As stated above, spectrum sensing is one of the main functions of the cognitive radio. Sensing accuracy is very difficult to achieve due to the factors like noise, multipath fading and hidden node problem. But the accuracy can be improved by reducing the effect of such factors. This is achieved by making a group of secondary users to cooperate with each other at the time of sensing. This is done by allowing the secondary users to act as relays. Relays are employed to retransmit the primary user's signal to the cognitive coordinator. Cognitive coordinator performs the final detection and take decision whether the primary user's signal is present or not, based on its own calculations. Relays can be used in two ways i.e either in decode or forward relay mode or in amplify and forward relay mode.

In decode and forward mode, the signal detectors are employed at the relays. So, the detection process actually takes place at each relay end. After this all the decision results are transmitted to the cognitive coordinator which further takes the decision about the primary user's presence or absence based on the fusion results of all the local decision results. This type of result fusion is known as hard fusion [8].

But in the case of amplify and forward relay mode, the signal detector is applied at the cognitive coordinator end. The relays only receive the primary user's signal, amplify that signal and then retransmit the amplified primary user's signal to the cognitive coordinator. All the received signals from the relays are then combined in some specific way and the resulting signal is then fed to the signal detector. This type of fusion is known as the soft fusion [4], [6]. Cognitive coordinator then take the decision about the presence or absence of the primary user's signal based on the detection results of the signal detector. Our analysis is for the amplify and forward relay mode .

4. SYSTEM MODEL

The system model of cognitive radio network is given in fig.1.The figure represent two types of channels i.e. sensing and reporting channels. h_{pr_1}, h_{r_1d} and h_{pd} can be considered as the channel gains of the corresponding channels between primary user, relays and cognitive coordinator. These channel gains are complex random variables varying according to the distribution in which they fall [19] i.e. either Rayleigh distribution for Rayleigh channel, Nakagami-n distribution for Nakagami-n fading channel and Nakagami-m distribution for Nakagami-m fading channel. The channel between the primary user and relay is also known as sensing channel and between the relay and cognitive coordinator is also known as reporting channel.

As the primary user starts using the band, cognitive radios or relays receive the signal of the primary user. Therefore in the first phase, all cognitive relays listen to the primary user signal. After this, the relays amplify the faded and noisy version of the received signal and retransmit it to the cognitive coordinator. The noise is added at the receiver of the relays as well as at the cognitive coordinator and this noise is considered as the AWGN signal. Each communication between cognitive relay and cognitive coordinator occurs in orthogonal channels to avoid the inter-channel interference. In orthogonal channels the cognitive coordinator receives independent signals from the primary user and the cognitive relays. These types of orthogonal channels can be realized by using Time division multiple access (TDMA) [20]. At the cognitive coordinator we use maximal ratio combining technique to combine all the received signals from various relays and from the primary user. Cognitive coordinator is equipped with the energy detector which compares the received signal strength with a pre-defined threshold. Based on the decision, the cognitive coordinator informs the cognitive radios of the presence or absence of primary user's activities. It is assumed that the primary user is not affected by cognitive radio transmission.

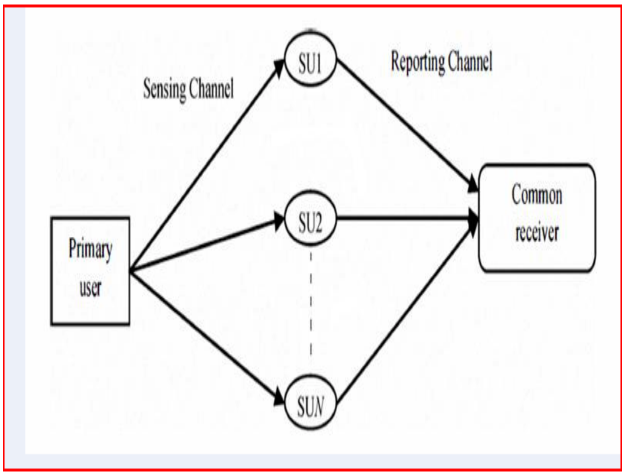

Fig.1 Cognitive radio network model

4.1 *Energy Detection*

It is a technique in which energy of transmitted signal is detected within a certain time period, further this detected energy is compared with a pre-defined threshold value [9],[10]. If detected energy is below than predefined threshold then it is assumed that licensed spectrum is free and if energy detected is above than the threshold value, it is assumed that the licensed spectrum is occupied by primary users so secondary users can not use the spectrum until primary users vacate the spectrum as shown in fig. 2.

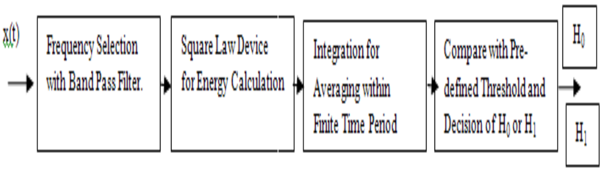

Fig.2 Block diagram of Energy detector

4.2 *DIRECT LINK WITHOUT RELAY*

In this case there will be only two nodes i.e. primary user and cognitive coordinator .This is the case when only a single cognitive radio acting as cognitive coordinator will take part in spectrum sensing and take decision based only on its own detection results. So this is the case of non cooperative spectrum sensing. The received signal by the cognitive coordinator denoted as y_{pd}, is given by $y_{pd} = h_{pd}\theta x + w_d$, where θ denotes the primary activity indicator, which is equal to 1 at the presence of primary activity, or equal to 0 otherwise, x is the transmitted signal from the primary user, and w_d is the noise signal at the cognitive coordinator which is assumed to be additive white Gaussian noise (AWGN). The received signal at the cognitive coordinator follows a binary hypothesis.

$$y_{pd} = \begin{cases} w_d & : H_0 \quad \theta = 0, \\ h_{pd}x + w_d & : H_1 \quad \theta = 1. \end{cases} \quad - \quad (1)$$

The received signal is first prefiltered by an ideal band-pass filter with center frequency fc and bandwidth W in order to normalize the noise variance [9]. The output of this filter is then squared and integrated over a time interval T to finally produce a measure of the energy of the received waveform. The output of the integrator, denoted Y, acts as the test statistic. The pdf of Y is given by

$$f_Y(y) = \begin{cases} \frac{1}{\Gamma(u)2^u} y^{u-1} e^{\frac{-y}{2}} & : H_0 \\ \frac{1}{2}\left(\frac{y}{2\gamma}\right)^{\frac{u-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{u-1}(\sqrt{2y\gamma}) & : H_1 \end{cases} \qquad (2)$$

Where Γ(.) is the gamma function , $I_v(.)$ is the v^{th} order modified Bessel function of the first kind, and u = TW is the time bandwidth product. γ is the signal to noise ratio at the cognitive coordinator and is given by $\gamma = \gamma_{pd} = |h_{pd}|^2 E_p/N_0$ in this case, where E_p is transmitted signal power from the primary user, N_0 is the single sided power spectral density (psd) of AWGN.

4.3 SINGLE RELAY WITH DIRECT LINK

In the case with a single relay, we have three nodes i.e. the primary user, the cognitive relay, and the cognitive coordinator. The received signal by the cognitive relay, denoted y_{pr}, is given by $y_{pr} = \theta\ x\ h_{pr} + w_r$, where w_r is the noise signal at the cognitive relay. The cognitive relay acts as an amplify and forward relay i.e it simply amplify and retransmit the noisy version of received signal to the cognitive coordinator. This type of data fusion is also known as soft fusion. The cognitive relay has a transmission power constraint E_r. Therefore, the amplification factor, β_r is given by $|\beta_r|2 = E_r/(\theta 2\ E_r|h_{pr}|2 + N_0)$.

Thus, the received signal at the cognitive coordinator, denoted y_{rd}, is given by $y_{rd} = \sqrt{\beta_r} y_{pr} h_{rd} + w_d$

$$y_{rd} = \theta\sqrt{\beta_r} h_{pr} h_{rd} x + \sqrt{\beta_r} h_{rd} w_d + w_d$$

$$y_{rd} = \theta hx + w$$

Where $h = \sqrt{\beta_r} h_{pr} h_{rd}$, and $w = \sqrt{\beta_r} h_{rd} w_d + w_d$ is the total effective noise at the cognitive coordinator. The received signal at the cognitive coordinator follows a binary hypothesis

$$y_{rd} = \begin{cases} w & : H_0 \qquad \theta = 0, \\ hx + w & : H_1 \qquad \theta = 1. \end{cases}$$

The output of the integrator, denoted Y, acts as the test statistic, pdf of which is given above. The difference lies in the end to end signal to noise ratio (S.N.R), denoted as γ_{ete} givenby $\gamma_{ete} = \frac{\gamma_{pr}\gamma_{rd}}{\gamma_{pr}+\gamma_{rd}+1} + \gamma_{pd}$, where $\gamma_{pr} = |h_{pr}|_2\ E_p/N_0$ and $\gamma_{rd} = |h_{rd}|_2 E_r/N_0$ are SNRs of the links from the primary user to the cognitive relay and from the cognitive relay to the cognitive coordinator, respectively. Derivation of γ_{ete} is given below.

4.4 END TO END SNR FOR SINGLE RELAY

Total signal plus noise power received at relay = $E_p * |h_{pr}|_2 + N_0$

Total signal plus noise power transmitted from relay = $(E_p * |h_{pr}|_2 + N_0) * |\beta_r|2$

Total signal plus noise power received at cognitive coordinator = $((E_p * |h_{pr}|_2 + N_0) * |\beta_r|2) * |h_{rd}|_2 + N_0$

$= E_p * |h_{pr}|_2 * |\beta_r|2 * |h_{rd}|_2 + N_0 *(|\beta_r|2 * |h_{rd}|_2 + 1)$

Where first part of addition denotes end to end signal power and second part denotes end to end noise power i.e.

End to end signal power = $E_p * |h_{pr}|_2 * |\beta_r|2 * |h_{rd}|_2$

End to end noise power = $N_0 *(|\beta_r|2 * |h_{rd}|_2 + 1)$

Therefore end to end SNR considering only relay

$$\frac{E_p *|h_{pr}|2 * |\beta_r|2 * |h_{rd}|2}{N_0 *(|\beta_r|2 * |h_{rd}|2 + 1)}$$

And by considering direct link SNR, total end to end SNR (γ_{ete}) becomes

$$\gamma_{ete} = \frac{E_p *|h_{pr}|2 * |\beta_r|2 * |h_{rd}|2}{N_0 *(|\beta_r|2 * |h_{rd}|2 + 1)} + \gamma_{pd}$$

It can be written as

$$\gamma_{ete} = \frac{\gamma_{pr}*|h_{pr}|2 * |\beta_r|2 * |h_{rd}|2}{(|\beta_r|2 * |h_{rd}|2 + 1)} + \gamma_{pd}$$

Multiplying both numerator and denominator by $\frac{E_r}{|\beta_r|^2}$, we get

$$\gamma_{ete} = \frac{\gamma_{pr} * E_r * |h_{rd}|2}{(E_r * |h_{rd}|2 + \frac{E_r}{|\beta_r|^2})} + \gamma_{pd}$$

$$\gamma_{ete} = \frac{\gamma_{pr} * \gamma_{rd} * N_0}{(\gamma_{rd} * N_0 + \frac{E_r}{|\beta_r|^2})} + \gamma_{pd}$$

$$\gamma_{ete} = \frac{\gamma_{pr} * \gamma_{rd} * N_0}{(\gamma_{rd} * N_0 + (E_p *|h_{pr}|2 + N_0))} + \gamma_{pd}$$

Taking N_0 common from both numerator and denominator we get,

$$\gamma_{ete} = \frac{\gamma_{pr}\gamma_{rd}}{\gamma_{pr}+\gamma_{rd}+1} + \gamma_{pd}$$

4.5 MULTIPLE COGNITIVE RELAYS

In case of multiple cognitive relays, we have n number of cognitive relays between the primary user and the cognitive coordinator. h_{pr_i}, h_{pd} and $h_{r_i d}$ are the channel gains of the corresponding channels between primary user, ith relay and cognitive coordinator respectively. All the cognitive relays simultaneously receive the primary user's signal through independent fading channels. Each cognitive relay i with amplification factor β_{ri} amplifies the received primary signal and then retransmits it to the cognitive coordinator where β_{ri} is given by

$$|\beta_{r_i}|_2 = \frac{E_{r_i}}{E_p|h_{pr_i}|^2 + N_0} .$$

The total end to end SNR in this case is given by

$$\gamma_{ete} = \gamma_{pd} + \sum_{i=1}^{n} \frac{\gamma_{pr_i}\gamma_{r_i d}}{1+\gamma_{pr_i}+\gamma_{r_i d}} ,$$

Where γ_{pr_i} and γ_{r_id} are the SNRs of the links from the primary user to the ith cognitive relay and from the ith cognitive relay to the cognitive coordinator, respectively.

At the cognitive coordinator, the energy detector compares the test statistic Y with a predefined threshold value also known as detection threshold denoted as λ. By applying the random variable theory [11],[12] and using pdf equation (2) of test statistic Y ,the probability of detection (Pf) and Probability of false alarm (Pf) can be evaluated as [9],[13],[14]

$$P_f = \text{Probability}\ (Y > \lambda : H0) = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}$$

$$P_d = \text{Probability}\ (Y > \lambda : H1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) .$$

where Qu(. , .) is the generalized Marcum-Q function [15],[16] and Γ(. , .) is the upper incomplete gamma function [15] .

5. FADING CHANNELS

As we can see that Probability of false alarm (Pf) depends only on u and λ both of which are independent of channel conditions and number of relays taking part in cooperation. So it is obvious that Pf will remain same for given value of u and λ under various channel and relay conditions. But in the case of probability of detection (Pd), it also depends on end to end SNR which further depends upon channel conditions i.e. channel gains and number of cognitive relays used for sensing. The channels for which we are going to study the spectrum sensing performance are flat fading channels or frequency non-selective fading channels. Multipath fading is due to the constructive and destructive combination of randomly delayed, reflected, scattered, and diffracted signal components. When a signal is transmitted through such a flat fading channel then its amplitude is modulated by the fading amplitude α, where α is a random variable (RV) with probability density function (PDF) pα(α), which depends on the radio propagation environment. So, the received instantaneous signal to noise power ratio (SNR) per symbol denoted as γ is given by γ = α2Es/N0 and average SNR per symbol denoted as $\bar{\gamma}$ is given by $\bar{\gamma}$ = $|\alpha^2|$ Es/No where $|\alpha^2|$ is the mean square value of α [17], [18].

5.1 *RAYLEIGH FADING CHANNEL*

The Rayleigh distribution is frequently used to model multipath fading with no direct line-of-sight (LOS) path and is known as Rayleigh fading [18]. In this case the channel fading amplitude α is distributed according to

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

This distribution is closely related to the central chi-square distribution i.e. if a and b are two zero mean statistically independent random variables , each having same variance, then a new random variable given by c= a2 + b2 will follow the central chi-square distribution with two degrees of freedom . Now, if we define a new random variable i.e d = $\sqrt{c}$ then this random variable will follow Rayleigh distribution [17].

5.2 *NAKAGAMI-N (RICE) FADING CHANNEL*

When the channel fading amplitude follows the Nakamani-n or rice distribution then it is known as Nakagami-n or Rician fading channel. It is often used to model propagation paths consisting of one strong direct line of sight component and many random weaker components due to multipath. The channel fading amplitude follows the distribution given as

$$p_\alpha(\alpha) = \frac{2(1+n^2)e^{-n^2}\alpha}{|\alpha^2|} \exp\left[-\frac{(1+n^2)\alpha^2}{|\alpha^2|}\right] I_0\left(2n\alpha\sqrt{\frac{1+n^2}{|\alpha^2|}}\right), \ \alpha \geq 0 .$$

Where n is the Nakagami-n fading parameter which ranges from 0 to ∞. n2 is the ratio between the power in the direct path to the power in the other scattered paths. For n=0, Nakagami-n reduces to Rayleigh fading and for n=∞ it becomes equivalent to no fading i.e. constant amplitude [18]. This distribution is also related to the non-central chi-square distribution. let p = q2 + r2 where q and r are statistically independent gaussian random variables with means m1 and m2 and same variance . in this case p will be having non-central chi-square distribution with non centrality parameter s2 = m12 + m22. Now if we define a new random variable i.e. t = $\sqrt{p}$ then t will follow Nakagami-n distribution [17].

5.3 *NAKAGAMI-M FADING CHANNEL*

Another distribution that is frequently used to characterize the statistics of signals transmitted through multipath fading channels is the Nakagami-m distribution [17]. Such fading channel is known as Nakagami-m fading channel. In this case the channel fading amplitude α is distributed according to [18]

$$p_\alpha(\alpha) = \frac{2m^m\alpha^{2m-1}}{|\alpha^2|^m\Gamma(m)} \exp\left(-\frac{m\alpha^2}{|\alpha^2|}\right), \qquad \alpha \geq 0.$$

Where m is Nakagami-m fading parameter which ranges from ½ to ∞. For m=1 this fading converges to Rayleigh fading and for m= ∞ it becomes equivalent to no fading.

6. SIMULATION RESULTS

The simulations are done for all the fading channels i.e Rayleigh fading, Nakagami-n fading and Nakagami-m fading. For simulations, MATLAB software is used. We have also used MAPLE software for some calculations. We have assumed that all the fading channels are independent and identically distributed (iid) for corresponding fading environments. The average SNR between each link is assumed to be 5 dB and value of u is set to be 2. For the simulation of curves between Pd and λ. λ is varied from 0 to 50. For the curves between the Pd and Pf, the values of λ for the corresponding Pf are calculated using MAPLE software and then the simulations are carried out in the MATLAB. Fig.3 and Fig.4 shows the variation of Pd w.r.t detection threshold λ and Pf for Rayleigh fading channels. Fig. 5 and Fig.6 shows the same variation for Nakagami-n fading for different values of n ranging from 0 to 5 for four relays. After n=5 i.e. 6,7 and so on, the variation as compared to n=5 is very insignificant and cannot be noticed easily. Fig. 7, 8 shows the same curves but in these figures the value of n is taken as constant i.e. n=5 and the results for different relay conditions are plotted. Fig.9 and Fig.10 shows the variation of Pd w.r.t detection threshold λ and Pf for Nakagami-m fading for different values of m ranging from 0 to 5 for four relays. After m=5 i.e. 6, 7 and so on, the variation as compared to m=5 is very insignificant and cannot be noticed easily. Fig. 11, 12 shows the same curves but in these figures the value of m is taken as constant i.e. n=5 and the results for different relay conditions are plotted.

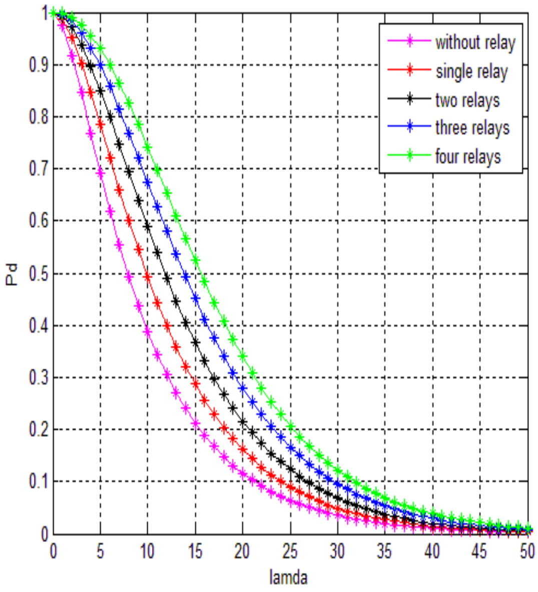

Fig. 3 **Pd vs λ for Rayleigh fading channel**

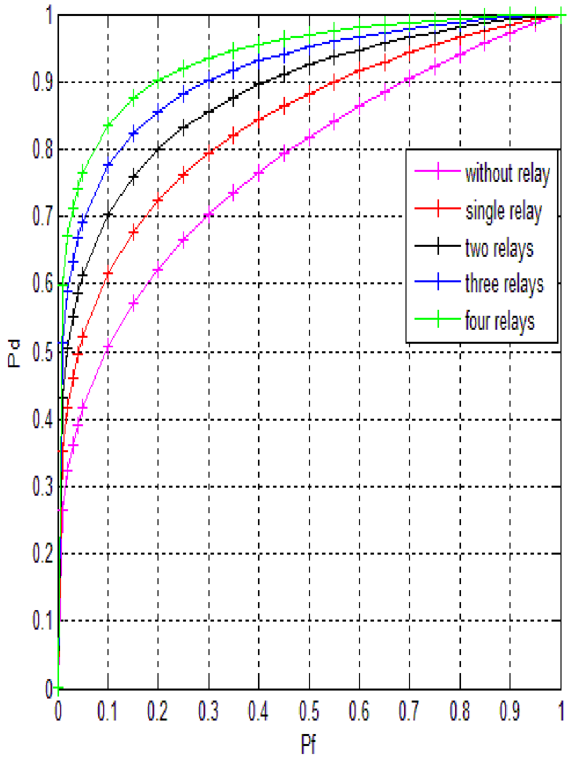

Fig. 4 **Pd vs Pf for Rayleigh fading channel**

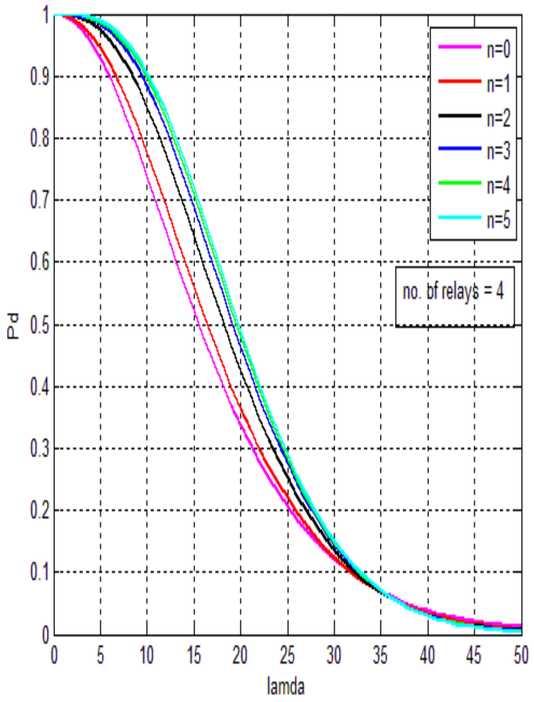

Fig. 5 **Pd vs λ for Nakagami-n fading for four relays**

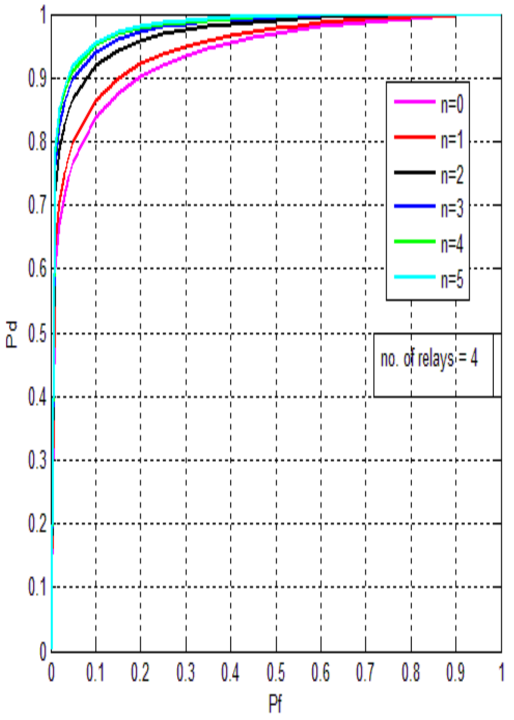

Fig. 6 **Pd vs Pf for Nakagami-n fading for four relays**

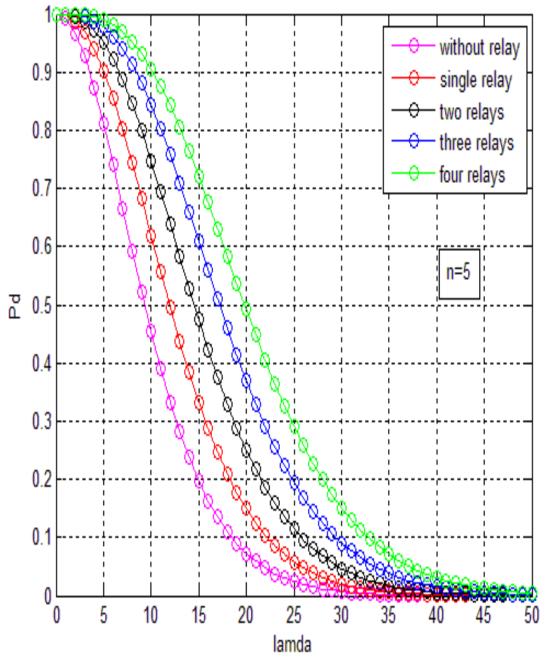

Fig. 7 **Pd vs λ for Nakagami-n fading for n=5**

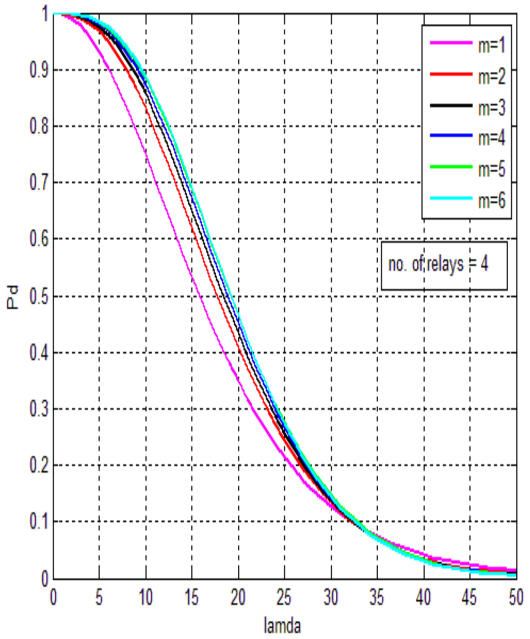

Fig. 9 **Pd vs λ for Nakagami-m fading for four relays**

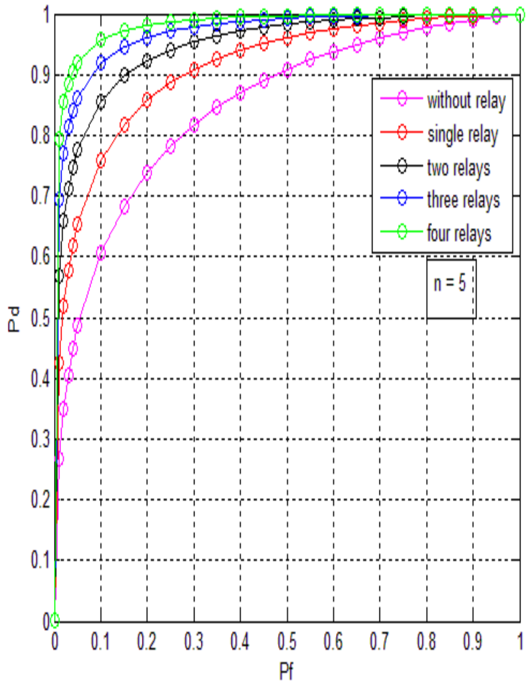

Fig. 8 **Pd vs Pf for Nakagami-n fading for n=5**

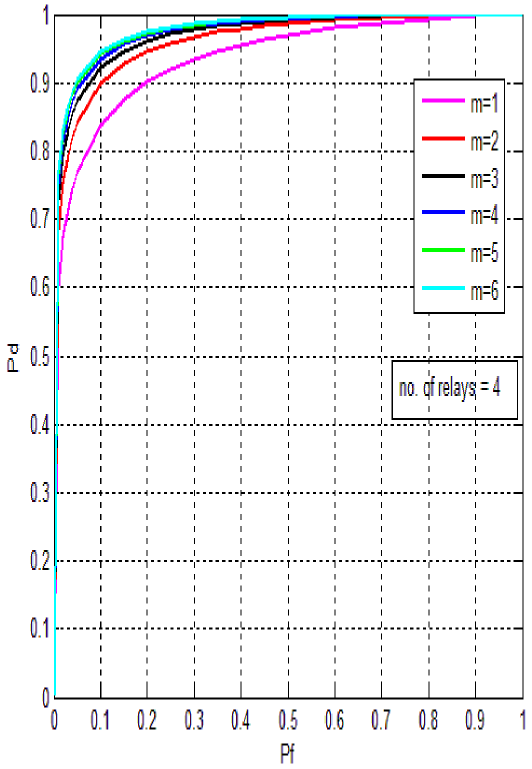

Fig. 10 **Pd vs Pf for Nakagami-m fading for four relays**

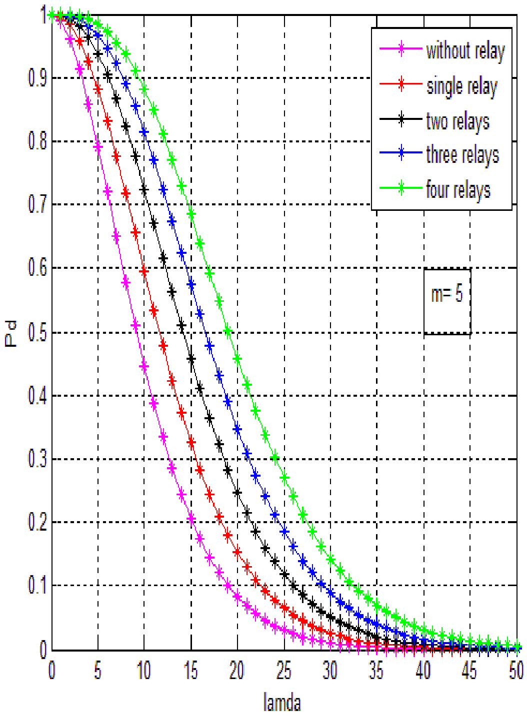

Fig. 11 **Pd vs λ for Nakagami-m fading for m=5**

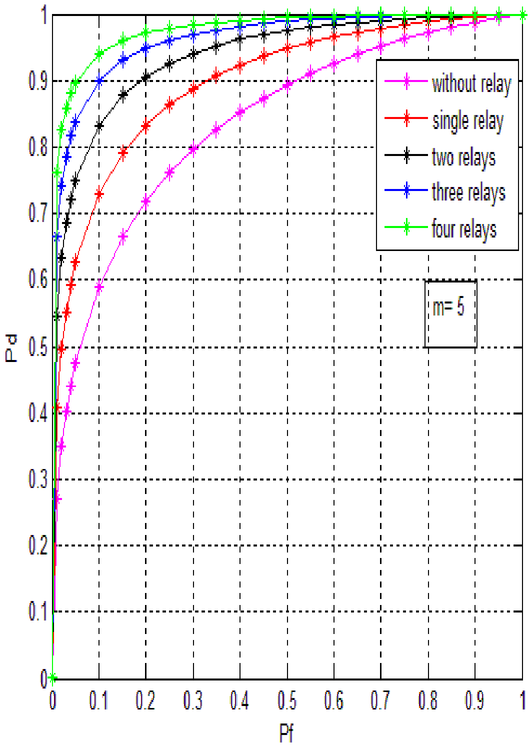

Fig. 12 **Pd vs Pf for Nakagami-m fading for m=5**

7 .CONCLUSION AND DISCUSSION

It can be seen that as the number of relays get increased, the detection performance gets improved i.e. probability of detection gets increased w.r.t the probability of false alarm and detection threshold for each fading channel. Also for Nakagami-n fading channel when the value of n is increased, the performance gets improved. Similarly for the case of Nakagami-m fading channel performance gets improved when value of m gets increased. It is obvious that if we will increase the value of average SNR then the performance will get better (results not shown here). Increase in the value of u i.e time bandwidth product will also lead to the increase in overall performance because u can only be increased by increasing T as W is signal bandwidth and cannot be altered for given signal which means that our signal is being examined for longer period by energy detector i.e. improvement in accuracy. But by doing so, the sensing period also gets increased which is undesirable as we need quick detection. Therefore, a trade-off between the sensing period and sensing accuracy occurs and value of u (or T) should be chosen suitably according to the given conditions to get desirable and optimum results.

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