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Cognitive Radio Performance Analysis and Threshold Optimization of Energy Detection over Inverse Gaussian Channel with Selection Combining Reception

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Abstract: The performance of spectrum sensing based on energy detection method in cognitive radio networks over inverse Gaussian channel for selection combining diversity technique is investigated. More precisely, exact and accurate analytical expressions for the average detection probability under different detection situation such as single channel i.e. single input single output and diversity reception are derived. The detection threshold parameter is optimized by minimizing the probability of error over several diversity branches. The outcomes shown in this paper, obviously shows the significant improvement in the detection of probability when optimized threshold parameter is applied. The impact of fading/shadowing parameters on the performance of energy detector is studied in terms of complimentary receiver operating characteristic curve. To verify the correctness of our analysis, the derived analytical expressions are verified via exact result and simulation.
Keywords: PDF; probability of detection; diversity; CROC; threshold; probability of false alarm

I. INTRODUCTION

Cognitive Radio has arisen as a very viable technique for well-organized use of the available spectrum by the secondary users. Basically it relies on the use of white space and it adapts its communication features as per the available spectrum. But this approach requires very stringent condition not to add any interference to primary communication services and free the spectrum whenever needed by licensed user. Therefore, the success of this technology depends upon how efficient and practical our sensing methods are. Among several sensing techniques such as waveform sensing, cyclo-stationary sensing and energy-based sensing, the energy detection approach is known to be simplest in term of its complexity and does not need any apriori information related to primary user communication. The performance of energy detection based approach depends on the selection of threshold criterion that, in turn, depends on the given geography. Thus, in order to extract the best performance, the threshold criterion needs to be optimized for a given fading channel.

Energy detector samples the non-coherent received signal energy over a time interval, compares with the conventional threshold and determines whether the unknown signal is present or not [1]. In [2], the shadowing case is considered that is characterized by Inverse Gassuain (IG) distribution (also called Wald distribution) and closed-form of detection probability is investigated with square-law combining technique but not with the selection combing technique. As well as adaptive spectrum sensing has not been used over IG distribution for selection combing. The authors Saman Atapattu et. al. in [3] consider Rayleigh and Nakagami multipath fading and they have optimized the detection threshold to minimize the probability of error. Authors in [4] have considered the case of cascaded channels with each of the link characterized by Rayleigh distribution and they have derived an average probability of detection for such case. They have also shown the detrimental effect of cascading. In [5], the statistical analysis of weather the signal present and absent of unknown deterministic signal using very simple and popular method so called energy detection are derived as non-central and central chi-square distributions respectively, by considering flat, band-limited and Gaussian white noise channel. The expression of probability of detection ( ) and probability of false alarm are also derived, shown in ROC curves for different time-bandwidths products. Kostylev et. al. in [6] give the analytical form expression for Rayleigh, Rice, Nakagami and other fading channels for probability of detection with respect to probability of false alarm. Different analytical approach is presented in [7-8] with no diversity and with diversities such as MRC, SC and switch-stay combining (SSC) for the performance of energy detector under different fading channels such as Rayleigh, Rice and Nakagami. In [9], performance of energy detector with equal gain combiner (ECG) is analysed under Nakagami fading channel. Further, Atapattu et. al. in [10], investigated

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performance of ED over fading channel. From above literature survey it is clear that multipath fading can be modeled as a Rayleigh, Rice or Nakagami distribution and shadowing is modeled as lognormal distribution [11], so we can say that most of the practical channel can be modeled as combination of multipath fading and lognormal shadowing i.e. composite channel.

To minimizing the probability of error is another important parameter to get optimized threshold for better spectrum efficiency. In [12], adaptive threshold algorithm has been analyzed and it gave better results in comparison to the conventional one and also provides trade-off between probability of detection and probability of false alarm. The problem of threshold parameter by minimizing the probability of error for cooperative spectrum sensing has been considered for Rayleigh channel in [13]. For minimizing the probability of miss detection and probability of false alarm, optimal threshold algorithm has been discussed in [14-15]. Zhang et. al in [14] considered weighted factor principle to trade off the probability of detection and probability of false alarm and Kozal et. al. in [15] considered spectrum utilization factor for calculation of adaptive threshold. In [16], the optimum value of probability of false alarm or probability of detection is attained by cooperating the group of users that have higher primary user's signal to noise ratio. Optimal threshold algorithm has been analyzed for OFDM signal using Neyman- Pearson and Welch's periodogram in [17-18] respectively.

The involvement of the present work is two-fold. Firstly, we present a closed-form expression of probability of detection over inverse Gaussian distribution with well-known diversity scheme such as Selection Combining (SC) nothing that, though maximum ratio combing (MRC) provides the best improvement in the system performance, however, SC enjoys the lowest implementation complexity. Further, an approximate closed-from PDF of SC technique has been derived and using this, the approximate closed-form of probability of detection is derived with SC technique. Secondly, we have optimized the threshold parameter for detecting the unknown signal for both with and without diversity scheme by minimizing the overall probability of error. A significant improvement in probability of detection is clearly shown with the use of optimized threshold parameter for all diversity branches.

II. SYSTEM MODEL

An In energy detection technique, secondary users (SUs) detects whether the primary user (PU) is present or not. The received signal, is passed through the band pass filter (BPF), followed by a squaring device for quantifying the received energy and then passed through the integrator that controls the observation interval, T as shown in fig. 1. Now, in order to decide whether signal is present or not, the output of the integrator will be compared with a predetermined threshold i. e. conventional threshold or adaptive threshold, λ.

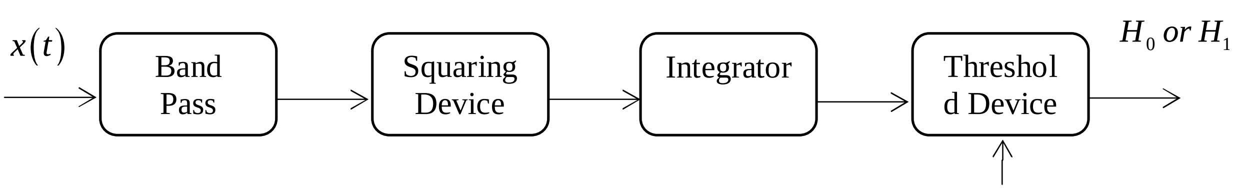

Fig. 1. Block diagram of energy detector

So, the received signal can be formulated by binary hypothesis with H_0 (signal is not present) and H_1 (signal is present) as

$$\begin{aligned} H_0 &: y(t) = n(t) \\ H_1 &: y(t) = h(t)x(t) + n(t) \end{aligned} \tag{1}$$

Where, $h(t)$ represents the channel gain between the transmitter and the receiver, $x(t)$ represents the band limited signal coming from the transmitter of unknown modulation format and $n(t)$ is additive white Gaussian noise (AWGN) $N(0,\sigma^2)$ where $\sigma^2 = N_0 W$, N_0 is one sided power spectral density (PSD) W is bandwidth of the system.

The output of energy detector can be expressed as $Y = \left(\frac{2}{N_0}\right)\int_0^T y^2(t)dt$. So, the corresponding to hypothesis H_0, the decision statistic can be expressed as [5, equation (2)]

$$Y = \left(\frac{2}{N_0}\right)\int_0^T n^2(t)dt = \sum_{k=1}^{2m}\left(\frac{n_k}{\sqrt{(N_0W)}}\right)^2 : H_0 \tag{2}$$

$$Y = X_1^{\ 2} + X_2^{\ 2} + X_3^{\ 2} + ... + X_{2m}^{\ \ 2} \tag{3}$$

Hence, Y under null hypothesis H_0, is square sum of $2m$ Gaussian random variable $X_i, i = 1,2,3.........2m$ with mean and variance as 0 and 1 respectively. Thus Y is chi-square distribution with the distribution

$$f_Y(y) = y^{n-1}\left(\frac{\exp\left(-\frac{y}{2}\right)}{\left(2^n\Gamma(n)\right)}\right) : H_0 \tag{4}$$

Here, $n = TW$ (time-bandwidth product).

Similarly, under alternate hypothesis H_1, the decision statistic, output of the detector is expressed as

$$Y = \left(\frac{2}{N_0}\right)\int_0^T \left(hx(t) + n(t)\right)^2 dt = \sum_{k=1}^{2m}\left(\frac{hx_k + n_k}{\sqrt{(N_0W)}}\right)^2 : H_1 \tag{5}$$

$$Y = X_1^{\ 2} + X_2^{\ 2} + X_3^{\ 2} + ... + X_{2m}^{\ \ 2} \tag{6}$$

Note that mean of X_i, under alternate hypothesis H_1, is $\frac{hx_k}{\sqrt{(N_0W)}}$. Thus, the chi-square distribution (non-central) with $\sigma^2 = 1$ is given as

$$f_Y(y) = \frac{1}{2}\left(\frac{y}{x^2}\right)^{\frac{n-1}{2}} \exp\left(-\frac{x^2 + y}{2}\right) I(y, x) : H_1 \tag{7}$$

Where, $x^2 = \sum_{k=1}^{2n}\left(\frac{hx_k}{\sqrt{N_0W}}\right)^2 = \frac{h^2}{N_0W}\sum_k^{2n} x_k^2 = \frac{2h^2S}{N_0W} = 2\gamma, \gamma = \frac{h^2S}{N_0}, S_x = \frac{\left(\frac{x_k}{\sqrt{2}}\right)^2}{W} = x_{k,rms}T$

Thus, knowing the probability density function (PDF) of decision statistic Y, one can easily estimate the probability of Y being less than certain threshold (λ_{th}) which is nothing but the outage probability of Y so, probability of false alarm, P_f is given as

$$P_f = P_r\left(Y > \lambda_{th}/H_0\right) = 1 - \int_0^{\lambda_{th}} f_{\gamma,H_0}(y)dy = \frac{\Gamma\left(n, \lambda_{th}/2\right)}{\Gamma(n)} \tag{8}$$

Probability of detection, P_d is given as

$$P_d = P_r\left(Y > \lambda_{th}/H_1\right) = 1 - \int_0^{\lambda_{th}} f_{\gamma,H1}(y)dy = Q_n\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) \tag{9}$$

Where, P_m is the probability of miss detection and $Q_n(.)$ is the generalized (n^{th} order) Marcum Q-function and $\Gamma(.)$ is the upper incomplete gamma function.

Marcum Q-function is defined as

$$Q_n(a,\chi)=\frac{1}{a^{n-1}}\int_{\chi}^{\infty}t^n\exp\left(-\frac{a^2+t^2}{2}\right)I_{n-1}(a,t)\,dt \tag{11}$$

Another form of generalized Marcum Q-function is given as [19]

$$Q_n\left(\sqrt{2\gamma},\sqrt{\lambda_{th}}\right)=\sum_{m=0}^{\infty}\exp(-\gamma)\frac{\gamma^m}{m!}\sum_{l=0}^{m+n-1}\left(\exp\left(-\frac{\lambda_{th}}{2}\right)\right)\left(\frac{(\lambda_{th}/2)^l}{l!}\right) \tag{12}$$

Equation (12) can be re-written as [20]

$$Q_n\left(\sqrt{2\gamma},\sqrt{\lambda_{th}}\right)=\sum_{m=0}^{\infty}\exp(-\gamma)\frac{\gamma^m}{m!}\frac{\Gamma(m+n,\lambda_{th}/2)}{\Gamma(m+n)}=\exp(-\gamma)\sum_{m=0}^{\infty}\frac{\gamma^m}{m!}\frac{\Gamma(m+n,\lambda_{th}/2)}{\Gamma(m+n)} \tag{13}$$

So, equation (4), can be written with the help of equation (13) as

$$P_d=Q_n\left(\sqrt{2\gamma},\sqrt{\lambda_{th}}\right)\approx\exp(-\gamma s)\sum_{l=0}^{\infty}\frac{(\gamma s)^l}{l!}\frac{\Gamma(n+l,\lambda_{th}/2)}{\Gamma(n+l)} \tag{14}$$

It is very much clear from equation (8) that the probability of false alarm P_f, is same over any fading channel as it does not depend upon the fading parameter. It only depends on the number of samples and threshold parameter. The expression in equation (8) and (9) are achieved by considering the channel as non-fading and thus channel parameter or gain h in equation (7) is assumed to be constant.

If the channel is characterized by multipath fading as an inverse Gaussian distribution (IG) with the diversity technique selection combining (SC). We consider independent and identically distributed (i.i.d.) channel scenario, for selection combing, probability distribution function (PDF) is defined as

$$f_{SC}(y)=N\left(F_Y(y)\right)^{N-1}\times f_Y(y) \tag{15}$$

where, $F_Y(y)$ and $f_Y(y)$ are the Cumulative distribution function (CDF) and probability distribution function (PDF) of RV Y, N is the number of diversity branches. The CDF and PDF for inverse Gaussian distribution are given as [21]

$$F_Y(y)=Q\left[\sqrt{\frac{\lambda}{y}}\left(1-\frac{y}{\theta}\right)\right]+\exp\left(\frac{2\lambda}{\theta}\right)Q\left(\sqrt{\frac{\lambda}{y}}\left(1+\frac{y}{\theta}\right)\right) \tag{16}$$

$$f_Y(y)=y^{-3/2}\sqrt{\frac{\lambda}{2\pi}}\exp\left(\frac{\lambda}{\theta}\right)\exp\left(-\lambda\left(\frac{y}{2\theta^2}+\frac{1}{2y}\right)\right) \tag{17}$$

Equation (16) is further re-expressed using property of Q-function $Q(-x)=1-Q(x)$ given by

$$f_{SC}(\gamma)=\begin{cases}\left\{N\left[Q\left(\sqrt{\frac{\lambda}{y}}\left(1-\frac{y}{\theta}\right)\right)+\exp\left(\frac{2\lambda}{\theta}\right)Q\left(\sqrt{\frac{\lambda}{y}}\left(1+\frac{y}{\theta}\right)\right)\right]^{N-1}\times\left(\frac{\lambda}{2\mu y^3}\right)^{1/2}\exp\left(-\frac{\lambda(y-\theta)^2}{2\theta^2 y}\right)\right\} & \gamma<\theta\\ \left\{N\left[\left(1-Q\left(\sqrt{\frac{\lambda}{y}}\left(1-\frac{y}{\theta}\right)\right)\right)+\exp\left(\frac{2\lambda}{\theta}\right)Q\left(\sqrt{\frac{\lambda}{y}}\left(1+\frac{y}{\theta}\right)\right)\right]^{N-1}\times\left(\frac{\lambda}{2\mu y^3}\right)^{1/2}\exp\left(-\frac{\lambda(y-\theta)^2}{2\theta^2 y}\right)\right\} & \gamma>\theta\end{cases} \tag{18}$$

The Q-function renders analytical difficulty while solving the integral using the above equation along with other function. The difficulty is overcome by using second order exponential approximation. Putting CDF and PDF in equation (15) and restoring to the second order exponential approximation of Q-function, the PDF of IG distribution for selection combining can be written as

$$f_{SC}(\gamma) = \begin{cases} \left\{ \begin{array}{l} \sum_{k=0}^{N-1}\sum_{r=0}^{K}\sum_{j=0}^{M} N\sqrt{\dfrac{\lambda}{2\pi}}\left({}^{N-1}C_k\right)\left({}^{K}C_r\right)\left({}^{M}C_j\right)\left(\dfrac{a_1}{2}\right)^{N-r-j-1}\left(\dfrac{a_2}{2}\right)^{r+j} \\ \exp\left(\dfrac{\lambda}{\theta}\{-b(M+j-k-r)+2M+1\}\right)\left(\gamma^{-3/2}\right)\exp\left(-\left\{\dfrac{\xi_1}{\gamma}+\xi_2\gamma\right\}\right) \end{array} \right\} & \gamma<\theta \\ \left\{ \begin{array}{l} \sum_{k=0}^{L-1}\sum_{i=0}^{K}\sum_{r=0}^{I}\sum_{j=0}^{M} N\sqrt{\dfrac{\lambda}{2\pi}}\left({}^{N-1}C_k\right)\left({}^{K}C_i\right)\left({}^{I}C_r\right)\left({}^{M}C_j\right)\left(\dfrac{a_1}{2}\right)^{N-r-j-1}\left(\dfrac{a_2}{2}\right)^{r+j} \\ \exp\left(\dfrac{\lambda}{\theta}\{-b(M+j-i-r)+2M+1\}\right)\left(\gamma^{-3/2}\right)\exp\left(-\left\{\dfrac{\xi_1}{\gamma}+\xi_2\gamma\right\}\right) \end{array} \right\} & \gamma>\theta \end{cases} \tag{19}$$

where, $M = N - K - 1$

$$\xi_1 = \frac{\lambda}{2}\left[b(N+r+j-1)+1\right]; \qquad \xi_2 = \frac{\lambda}{2\theta^2}\left[b(N+r+j-1)+1\right]$$

$$\xi_3 = \frac{\lambda}{2}\left[b(N-K+r+i+j-1)+1\right]; \quad \xi_4 = \frac{\lambda}{2\theta^2}\left[b(N-K+r+i+j-1)+1\right]$$

$$A_1 = N\sqrt{\frac{\lambda}{2\pi}}\left({}^{N-1}C_k\right)\left({}^{K}C_r\right)\left({}^{M}C_j\right)\left(\frac{a_1}{2}\right)^{N-r-j-1}\left(\frac{a_2}{2}\right)^{r+j}$$

$$A_2 = N\sqrt{\frac{\lambda}{2\pi}}\left({}^{N-1}C_k\right)\left({}^{K}C_i\right)\left({}^{I}C_r\right)\left({}^{M}C_j\right)\left(\frac{a_1}{2}\right)^{N-r-j-1}\left(\frac{a_2}{2}\right)^{r+j}$$

$$x_1 = -b(M+j-k-r)+2M+1; \qquad x_2 = -b(M+j-i-r)+2M+1$$

$$\theta = \exp\left(\frac{\mu}{\xi}+\frac{\sigma^2}{2\xi^2}\right) \;\&\; \lambda = \frac{\theta}{\exp\left(\dfrac{\sigma^2}{\xi^2}\right)-1} \text{ and } \xi = 10/\ln(10)$$

Now, equation (18) becomes

$$f_{SC}(\gamma) = \begin{cases} A_1\gamma^{-3/2}\exp\left(\dfrac{\lambda}{\theta}x_1\right)\exp\left(-\dfrac{\xi_1}{\gamma}-\xi_2\gamma\right) & \gamma<\theta \\ A_2\gamma^{-3/2}\exp\left(\dfrac{\lambda}{\theta}x_2\right)\exp\left(-\dfrac{\xi_3}{\gamma}-\xi_4\gamma\right) & \gamma>\theta \end{cases} \tag{20}$$

Here, $\mu > 0$ is the mean, θ is the mean of fluctuations and $\lambda > 0$ is the shape parameter. As λ tends to ∞, the IG distribution becomes more likely to Gaussian distribution.

III. AVERAGE PROBABILITY OF DETECTION

When the channel gain varies, the average probability of detection can be calculated by averaging P_d in equation (9) over the SNR distribution as [2]

$$\overline{P}_d = \int_0^\infty P_d\left(\gamma, \lambda_{th}\right) f\left(\gamma\right) d\gamma = \int_0^\infty Q_n\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) f_{SC}\left(\gamma\right) d\gamma \tag{21}$$

In this section, we discuss the performance of energy detector with diversity combing method i.e. for selection combining. The combiner selects that branch which is having the strongest signal to noise ratio (SNR) among all diversity branches. The instantaneous SNR at the output of the selection combiner is $\gamma_{SC} = \max\left\{\gamma_1, \gamma_2 \ldots\ldots, \gamma_N\right\}$, where γ_N is the SNR in the N^{th} branch.

Probability of false alarm will remain same as given in equation (8). $\overline{P}_d$ with selection combining diversity is derived by substituting equation (14) and (20) into (21) as

$$\overline{P_d} = \left\{ \begin{array}{l} A_1 \exp\left(\dfrac{\lambda}{\theta} x_1\right) \displaystyle\int_0^\theta \gamma^{-3/2} \exp\left(-\dfrac{\xi_1}{\gamma} - \xi_2 \gamma\right) \exp\left(-\gamma s\right) \sum_{l=0}^\infty \dfrac{\left(\gamma s\right)^l}{l!} \dfrac{\Gamma\left(n+l, \lambda_{th}/2\right)}{\Gamma\left(n+l\right)} d\gamma + \\ A_2 \exp\left(\dfrac{\lambda}{\theta} x_2\right) \displaystyle\int_\theta^\infty \gamma^{-3/2} \exp\left(-\dfrac{\xi_3}{\gamma} - \xi_4 \gamma\right) \exp\left(-\gamma s\right) \sum_{l=0}^\infty \dfrac{\left(\gamma s\right)^l}{l!} \dfrac{\Gamma\left(n+l, \lambda_{th}/2\right)}{\Gamma\left(n+l\right)} d\gamma \end{array} \right\} \tag{22}$$

Using the relation $\int_0^\infty x^{v-1} \exp\left(-\beta x^p - \dfrac{\gamma}{x^p}\right) dx = \dfrac{2}{p}\left(\dfrac{\gamma}{\beta}\right)^{\frac{\gamma}{2p}} K_{v/p}\left(2\sqrt{\beta\gamma}\right)$; $\beta > 0, \operatorname{Re}\gamma > 0$

and $\Gamma\left(t, x, b\right) = \int_x^\infty t^{x-1} e^{-t-(b/t)} dt$; $x > 0, \operatorname{Re} b > 0$ with notations has their usual meaning and applied in equation (22), we get the expression for the average probability of detection as

$$\overline{P_d} \approx \left[\left(A_1 \exp\left(\frac{\lambda}{\theta} x_1\right)\right) \sum_{l=0}^\infty \frac{s^l}{l!} \frac{\Gamma\left(n+l, \lambda_{th}/2\right)}{\Gamma\left(n+l\right)} \left\{ \begin{array}{l} 2\left(\dfrac{\xi_1}{s+\xi_2}\right)^{l-1/2} K_{l-1/2}\left(2\sqrt{\left(s+\xi_1\right)\xi_1}\right) - \\ \left(\dfrac{1}{\left(s+\xi_2\right)^{l-1/2}}\right) \Gamma\left(l-1/2, T_0, \xi_1\left(s+\xi_2\right)\right) \end{array} \right\} \right]$$
$$+ \left[\left(A_2 \exp\left(\frac{\lambda}{\theta} x_2\right)\right) \sum_{l=0}^\infty \frac{s^l}{l!} \frac{\Gamma\left(n+l, \lambda_{th}/2\right)}{\Gamma\left(n+l\right)} \left(\frac{1}{\left(s+\xi_4\right)^{l-1/2}}\right) \Gamma\left(l-1/2, y_0, \xi_3\left(s+\xi_4\right)\right) \right] \tag{23}$$

Where, $K_{l-1/2}\left(\varepsilon\right)$ denotes the modified Bessel Function of the second kind with order $l-1/2$.

IV. THRESHOLD OPTIMIZATION

If the threshold is too low, it will it will give an overestimate of the presence of the signal and thus false alarm will be high resulting in loss of scarce primary spectrum. If the threshold level is too high, then, the primary signal present could also be treated as noise and probability of detection will decrease.. The sensing time is optimized to enhance the throughput. In [13], the problem of optimizing threshold parameter by minimizing error probability for cooperative sensing has been considered for Rayleigh channel. In this section, our goal is to optimize the detection threshold parameter by minimizing probability of error for lognormal channel with diversity scheme. The probability of error can be expressed as [3], [12], [13]

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$$P_e = P(H_0)P_f + P(H_1)P_m \tag{24}$$

Substituting the value of P_f and P_m for single input single output (SISO) and for selection combining diversity. The optimum threshold can be obtained by differentiating error probability and equating it to zero, i.e. $\partial(P_e)/\partial(\lambda_{th}) = 0$. We can observe that the total error probability given by equation (23) has a global minimum with respect to λ_{th} by minimizing P_e, given by equation (23) $\lambda_{opt} = \arg\min_{\lambda_{th}}(P_e)$. It can be solved by $\partial(P_e)/\partial(\lambda_{th}) = 0$. Thus considering apriori probability of both the hypothesis to be same, we have

$$\frac{\partial P_f}{\partial \lambda_{th}} + \frac{\partial P_m}{\partial \lambda_{th}} = 0 \tag{25}$$

The first term $\delta P_f / \delta\lambda_{th}$ is obtained by differentiating equation (8) w.r.t λ_{th}. It is obtained by restoring the identity $\delta\left[\Gamma(a,z)\right]/\delta\lambda_{th} = -\exp(-z)z^{a-1}$ [15]. So using this relation, we can find $\delta P_f / \delta\lambda_{th}$ as

$$\frac{\delta P_f}{\delta\lambda_{th}} = \frac{\lambda_{th}{}^{n-1}\exp(-\lambda_{th}/2)}{2^n\Gamma(n)} \tag{26}$$

$$\frac{\delta \overline{P_m}}{\delta\lambda_{th}} = \frac{\delta\left(1-\overline{P_d}\right)}{\delta\lambda_{th}} = -\frac{\delta\overline{P_d}}{\delta\lambda_{th}} \tag{27}$$

Substituting equation (22) into equation (26) and after some mathematical calculation equation (24) becomes as

$$\begin{aligned}
&\frac{\lambda_{th}{}^{n-1}\exp(-\lambda_{th}/2)}{2^n\Gamma(n)} - A_1\frac{\theta}{x_1}\left\{\exp\left(\frac{x_1\lambda}{\theta}\right)\sum_{l=0}^{\infty}\frac{\Gamma(n+l,\lambda_{th}/2)}{\Gamma(n+l)} + \sum_{l=0}^{\infty}\frac{(-1)^{n+l-1}\Gamma(n+l)}{2^{n+l-1}(x_1/\theta-1/2)^{n+l-1}}\right\}\times \\
&\left\{2\left(\frac{\xi_1}{s+\xi_2}\right)^{l-1/2}K_{l-1/2}\left(2\sqrt{(s+\xi_1)\xi_1}\right)-\left(\frac{1}{(s+\xi_2)^{l-1/2}}\right)\Gamma\left(l-1/2,T_0,\xi_1(s+\xi_2)\right)\right\}+ \\
&A_2\frac{\theta}{x_2}\left\{\exp\left(\frac{x_2\lambda}{\theta}\right)\sum_{l=0}^{\infty}\frac{\Gamma(n+l,\lambda_{th}/2)}{\Gamma(n+l)} + \sum_{l=0}^{\infty}\frac{(-1)^{n+l-1}\Gamma(n+l)}{2^{n+l-1}(x_2/\theta-1/2)^{n+l-1}}\right\}\times \\
&\left\{\left(\frac{1}{(s+\xi_4)^{l-1/2}}\right)\Gamma\left(l-1/2,y_0,\xi_3(s+\xi_4)\right)\right\} = 0
\end{aligned} \tag{28}$$

Solving equation (28) numerically, we get the optimum value of λ_{th} and by using optimum value of threshold (λ_{th}), we can get the optimum value of probability of miss, probability of detection as well as optimum probability of error using equation (28).

V. DISCUSSION

The exact numerical results are obtianed by replacing the PDF of the single intgral equation (21) by equation (15) and then solving integral using MATLAB. Complementry reciever operating charachertisic under different branches for selection combing technique over IG distribution is plotted at $\sigma = 4\,dB$ and $\mu = 5\,dB$ without use of adaptive threshold as shown in fig. 2. The plot also includes exact result and Monte Carlo simulation for validation purpose.

The optimization of detection threshold parameter has been discussed in fig. 4. The inverted bell-shaped plot has been obtained for several values of SNR (-10, 0-, 5, 10) in dB and light shadowing and heavy shadowing cases have been considered. It is observed from the fig. 4 that the probability of error given by $P_e = P(H_0)P_f + P(H_1)P_m$ has the global minimum with respect to threshold (λ_{th}).

The probability of detection verses received average SNR (dB) is plotted as shown in fig. 5 for fixed and optimized (or adaptive) detection threshold. It is evident from the fig. 5 that optimized detection threshold significantly improves the detection probability from the fixed threshold. As well as the number of branches increases i.e. form N=1 to 3, probability of detection improves in a better way for optimized threshold in comparison with fixed threshold.

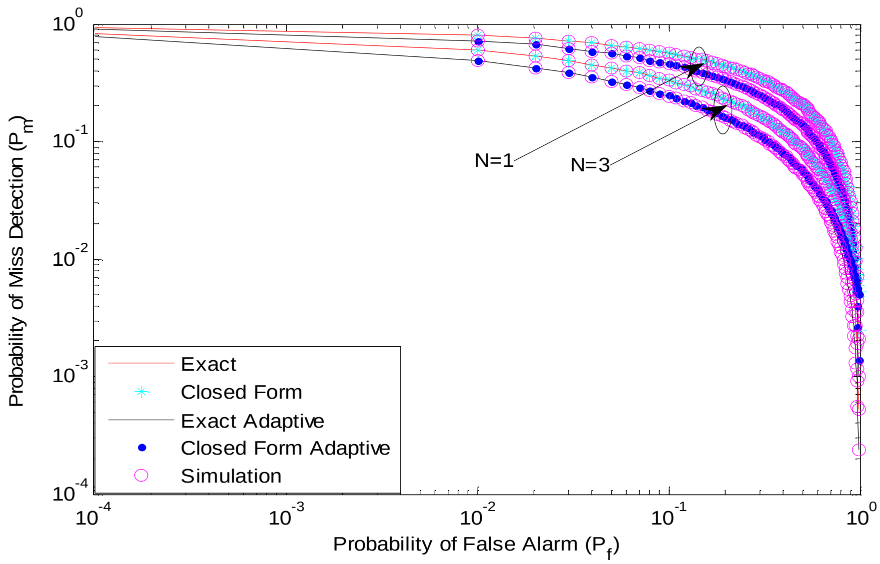

Fig. 2. Probability of miss detection verses probability of false alarm for SC

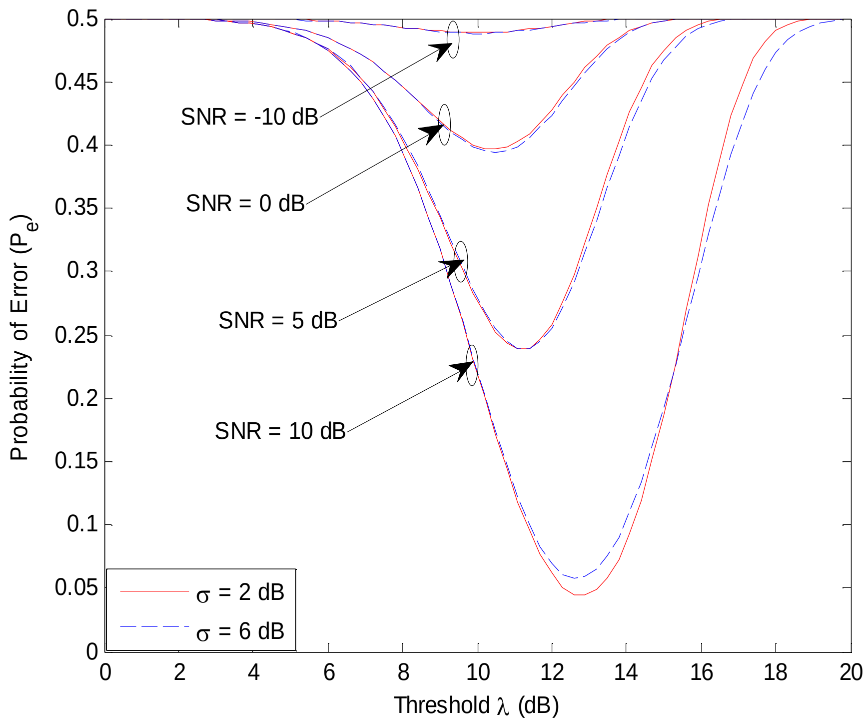

Fig. 3. Probability of error verses threshold

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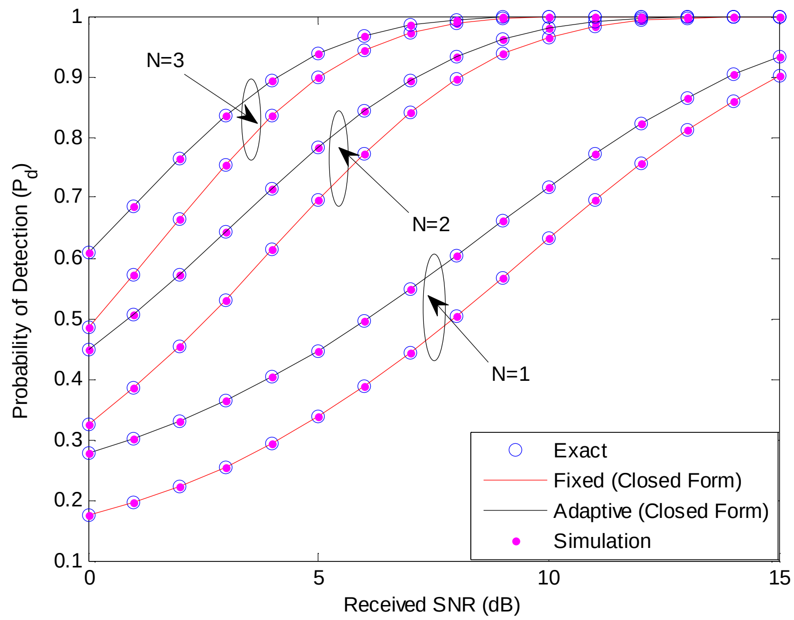

Fig. 4. Probability of detection verses received SNR (dB)

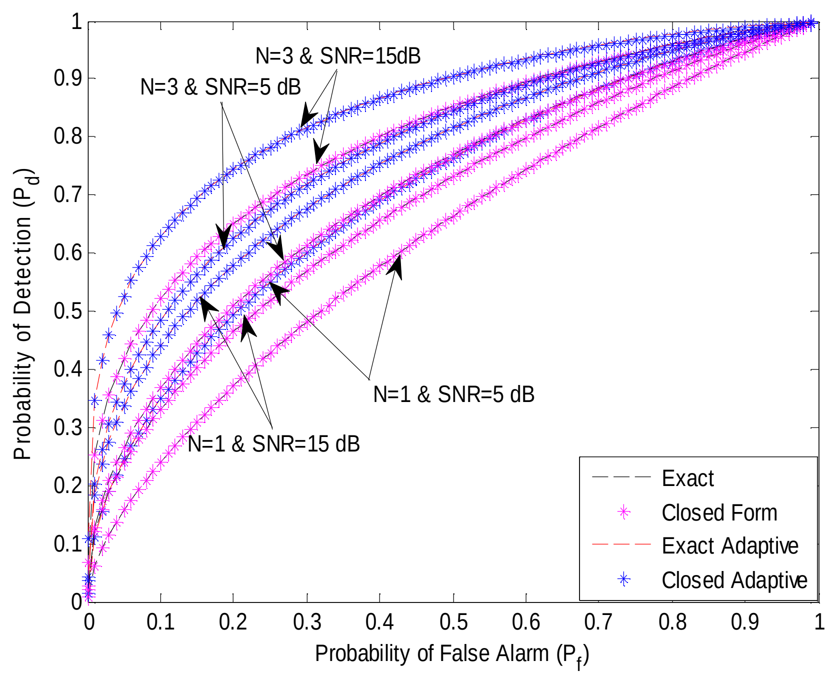

Fig. 5. ROC under different selection combining branches

VI. CONCLUSIONS

In this paper, we have offered accurate analytical expressions for probability of detection over inverse Gaussian channel for both SISO and diversity reception. Additional, we have optimized the detection of probability of threshold parameter by minimizing the probability of error. After applying the optimized threshold parameter, a very significant improvement in probability of detection has been demonstrated. Hence form the overall paper it is very much clear that the CROC plots have shown the great improvement of probability of miss detection with respect of probability of false alarm with optimized threshold parameter.

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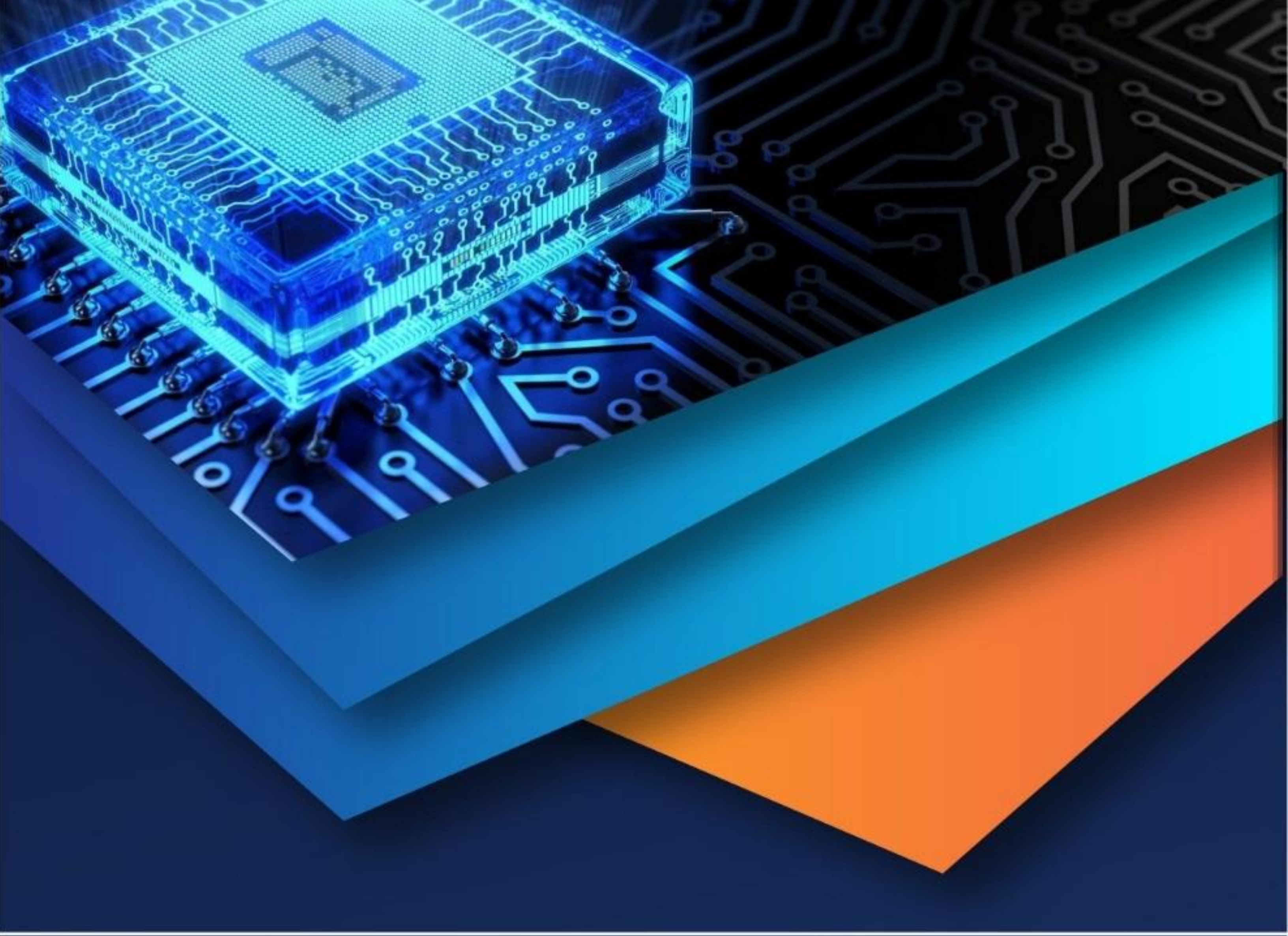

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