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Performance Advancement Of Energy Detection In Cognitive Radio Over Composite Shadowed Nakagami-M Fading With Maximum Ratio Combining Reception

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ABSTRACT: The spectrum sensing is the key function of cognitive radio and energy detector is the most popular method used for spectrum sensing. Detection of the availability of unused spectrum for the secondary user becomes difficult when the channel is affected by composite fading. In this paper, analytical expressions of average probability of detection and average area under the receiver operating characteristic over Nakagami-m/log-normal with maximum ratio combining diversity are derived using Gaussian-Hermite integration approximation. In addition, an optimized threshold has been incorporated to overcome the problem of spectrum sensing even at low signal-to-noise ratio. To authenticate the exactness of exact results and derived analytical expressions, simulations are integrated.

Keywords: Diversity; Cognitive radio; energy detection; probability density function; average probability of detection; average AUC; CROC

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I. INTRODUCTION

In advance wireless communication systems, the performance of energy detection (ED) with non-cooperative and cooperative sensing has been extensively studied in the presence of fading environments for single input single output and multiple channel reception. The performance of ED with square law combining and square law selection over Nakagami-m has been studied [2]. Based on moment generating function, analytical expressions of the average probability of detection ($\overline{P_D}$) over Rician and Nakagmai-m channels at different diversity has been derived such as maximum ratio combining, selection combing (SC), equal gain combing (EGC) and SLC [3]. Under Nakagami-m channel with EGC receiver, performance of ED is investigated in terms of receiver operating characteristic (ROC) curve [4]. ED-based performance analysis and threshold optimization with SC over inverse-Gaussian (IG) channel has been discussed [5]. The analytical expressions of average area under the receiver operating characteristic (AUC) curve over Nakagami-m channel with MRC, SLC and SC has been derived [6]. Performance analysis of Wald distribution with SLC is investigated in [7].

The shadowing can considerably reduce the performance of ED in current practical AWCS. Hence, the combination of both multipath and shadowing fading is called composite multipath/shadowing fading channel that occur very frequently in most of the realistic wireless environments, degrade the performance of the channels. Shadowing is modeled by log-normal distribution [8, 9]. The performance analysis of SS in CR over Rician/log-normal is studied [10]. In [11, 12], log-normal is approximated by Gamma distribution and the performance of ED in K and generalized-K fading channels was discussed. Again log-normal can also be approximated by IG and performance analysis of ED is examined with different diversity [13]. The performance of ED over composite fading channel is measured with mixture Gamma distribution [14]. In order to sense the PUs very quickly, SUs are allocated into multiple clusters then the performance analysis of cooperative spectrum sensing (CSS) is examined for multipath/shadowed fading channel [15]. The analytical expressions of $\overline{P_D}$ and average AUC ($\overline{A}$) are derived for different diversity such as MRC, EGC and SC over Gamma/shadowed Rician channels and performances are measured in terms of complementary ROC curves and average complementary AUC curves [16].

Minimizing the total probability of error is significant parameter to get optimized threshold for better spectrum sensing. Hence, threshold is varied in accordance with the fluctuation of received signal is called optimized threshold. Optimized threshold algorithm has been analyzed, it gave better results in comparison to the conventional one and provide trade-off between the probability of detection (P_D) and probability of false alarm (P_{FA}) [17, 18]. The problem of optimized threshold parameter by minimizing the total probability of error for CSS has been consider for Rayleigh channel in [19]. By minimizing the probability of miss detection (P_{MD}) and P_{FA} , optimized threshold algorithm has been discussed [20, 21]. Optimized double threshold (ODT) overcomes the problem of sensing failure for CSS. ODT is better in comparison to the conventional threshold, which provides better spectrum sensing even at very low SNR but with multiple EDs [22]. Optimized threshold obtained by minimizing the total probability of error with improved ED and SC is used at each detector [23, 24]. The performance analysis and optimize threshold for CR based IoTs devices [25].

In this paper, we present an analytical expression of average probability of detection and average area under the receiver operating characteristic over composite NL fading channel with MRC diversity. MRC gives the best performance among the other diversity techniques. Furthermore, we have optimized the threshold parameter for detection of unknown signal for MRC diversity scheme by minimizing the total probability of error. A significant improvement in the probability of detection is demonstrated the use of optimized threshold parameter for all diversity branches.

The rest of the paper is organized as follow. System and channel model is discussed in section 2. Energy detection with MRC diversity reception is described mathematically in section 3. In section 4, the optimization of threshold parameter is explained. Section 5 gives the results and discussion followed by conclusion in Section 6.

II. SYSTEM AND CHANNEL MODEL

Consider a narrow band composite signal is detected, the received signal $x(t)$, which comprises either noise only or unknown deterministic signal and noise as shown in Fig. 1, can be represented as [1]

$$x(t)=\begin{cases} w(t) & ;H_0 \\ h\,s(t)+w(t) & ;H_1 \end{cases} \tag{1}$$

where, $s(t)$ denotes unknown deterministic signal, h is the channel gain and $w(t)$ is an AWGN. Furthermore, in the detection of signal either signal is absent or signal is present and it is represented by the hypothesis called H_0, null hypothesis and H_1, alternate hypothesis respectively. In ED, first filter the signal, square it and integrate over the time interval T. The output of the integrator, Λ acts as test statistic that decides whether the received signal energy corresponds to noise energy $w(t)$ or energy of both $s(t)$ and $w(t)$. At the end of ED, Λ compares with the threshold (λ_{th}) and if $\Lambda < \lambda_{th}$, signal is absent otherwise present.

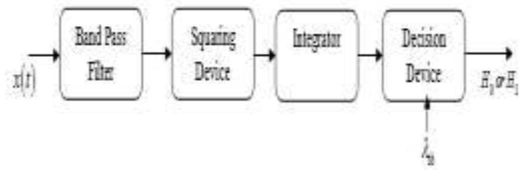

Fig. 1 Block diagram for the determination of test statistic

Under H_0, Λ follows a central chi-square distribution with $2d$ degrees of freedom. Similarly, under H_1, Λ follows a non-central chi-square distribution with $2d$ degrees of freedom and 2γ non-centrality parameter [1]. Thus, PDF of Λ can be written as

$$p_\Lambda(y/\gamma)=\begin{cases} \dfrac{1}{2^d\Gamma(d)}y^{d-1}e^{-y/2} & ;H_0 \\ \dfrac{1}{2}\left(\dfrac{y}{2\gamma}\right)^{d-1/2} e^{-\left(\frac{y+2\gamma}{2}\right)} I_{d-1}\left(\sqrt{2y\gamma}\right) & ;H_1 \end{cases}$$

(2)

where, $d=TW$ is the time-bandwidth product and W, bandwidth of the system, $\gamma=|g|^2 E_S^2/N_0$ γ is the received SNR with E_S be the signal energy and N_0 is the one-sided power spectral density (PSD). $I_q(.)$, q^{th} order modified Bessel function of first kind. For ED, with λ_{th} as the threshold of detection, the probability of false alarm (P_{FA}) and probability of detection (P_D) are defined [2] by equations (3) and (4) respectively as

$$P_{FA}\left(\lambda_{th}\right) = P_r\left(\Lambda > \frac{\lambda_{th}}{H_0}\right) = \frac{\Gamma\left(d, \lambda_{th}/2\right)}{\Gamma\left(d\right)} \quad (3)$$

$$P_D\left(\gamma, \lambda_{th}\right) = P_r\left(\Lambda > \frac{\lambda_{th}}{H_1}\right) = Q_d\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) \quad (4)$$

where, $\Gamma(.,.)$ is the incomplete Gamma function, $\Gamma(.)$ is the Gamma function, $Q_d(.,.)$ is the d^{th} order generalized Marcum Q-function and P_{MD} is the probability of miss-detection. Generalized Marcum Q-function is defined as [26]

$$Q_p\left(\alpha, \psi\right) = 1/\left(\alpha^{p-1}\right)\int_{\psi}^{\infty} \tau^p \exp\left(-\left(\alpha^2 + \tau^2\right)/2\right) I_{p-1}\left(\alpha, \tau\right) d\tau$$

$$Q_p\left(\alpha, \psi\right) = 1/\left(\alpha^{p-1}\right)\int_{\psi}^{\infty} \tau^p \exp\left(-\left(\alpha^2 + \tau^2\right)/2\right) I_{p-1}\left(\alpha, \tau\right) d\tau \quad (5)$$

Alternative way to represent generalized Marcum Q-function is given in (4.74) of [8] as

$$Q_d\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) = \sum_{k=0}^{\infty} \exp(-\gamma)\left(\gamma^k / k!\right) \sum_{l=0}^{k+d-1} \left(\exp\left(-\lambda_{th}/2\right)\right)\left(\left(\lambda_{th}/2\right)^l / l!\right) \quad (6)$$

Equation (6) can be re-written in (8.352-2) of [26] as

$$Q_d\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) = \sum_{k=0}^{\infty} \exp(-\gamma)\frac{\gamma^k}{k!}\frac{\Gamma\left(k+d, \lambda_{th}/2\right)}{\Gamma\left(k+d\right)} = \exp(-\gamma)\sum_{k=0}^{\infty}\frac{\gamma^k}{k!}\frac{\Gamma\left(k+d, \lambda_{th}/2\right)}{\Gamma\left(k+d\right)} \quad (7)$$

So, equation (4), can be written with the help of equation (7) as

$$P_D\left(\gamma, \lambda_{th}\right) = Q_d\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) \approx \sum_{k=0}^{\infty}\frac{\gamma^k}{k!}\frac{\Gamma\left(d+k, \lambda_{th}/2\right)}{\Gamma\left(d+k\right)}\exp\left(-\gamma\right) \quad 8)$$

The composite PDF of received SNR is achieved by averaging the conditional PDF of Nakagami-m distribution over log-normal distribution. The conditional Nakagami-m distribution [8] is given by

$$f_\gamma\left(\gamma|v\right) = \frac{m^m \gamma^{m-1}}{\Gamma(m) v^m} exp\left(-\frac{m\gamma}{v}\right) \quad ;\gamma \ge 0 \quad (9)$$

where, v is the average SNR at the receiver, m is the Nakagami-m fading parameter ($m \ge 1/2$). Short-term fading is mitigated through micro-diversity approaches using multiple antennas at the receiver [9]. When MRC diversity is integrated, the overall SNR at the output of the receiver is sum of SNR of all the individual branches multiplied by their proportional weights. The instantaneous SNR of MRC is given as

$$\gamma_{MRC} = \sum_{b=1}^{B} \gamma_b \quad (10)$$

where, B is the total number of branches used in the diversity combiner and γ_b is the instantaneous SNR of the b^{th} branch. Assuming i.i.d branches, the PDF of γ_{MRC} can be represented in [27] as

$$f_{\gamma_{MRC}}\left(\gamma|v\right) = \frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB) v^{mB}} exp\left(-\frac{m\gamma}{v}\right) \quad ;\gamma > 0$$

(11)

Shadowing is caught by log-normal distribution and its PDF is given by [8]

$$f_v\left(v\right) = \frac{1}{\sigma v\sqrt{2\pi}} exp\left(-\frac{\left(lnv - \mu\right)^2}{2\sigma^2}\right) \quad (12)$$

where, μ , σ are mean and standard deviation of random variable (RV) [28]. Averaging the conditional PDF of equation (11) w.r.t PDF of equation (12) as expressed in equation (13)

$$f_{\gamma_{MRC}}\left(\gamma\right) = \int_0^{\infty} f_{\gamma_{MRC}}\left(\gamma|v\right) f_v\left(v\right) dv \quad (13)$$

Substituting equations (11) and (12), into equation (13), we have

$$f_{\gamma_{MRC}}\left(\gamma\right) = \int_0^{\infty} \frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB) v^{mB}} exp\left(-\frac{m\gamma}{v}\right)\frac{1}{\sigma v\sqrt{2\pi}} exp\left(-\frac{\left(lnv-\mu\right)^2}{2\sigma^2}\right) dv \quad (14)$$

It is statistically inflexible to get closed-from expression of equation (14). Hence, to achieved closed-form expression, approximate equation (14) by well know integration approximation called Gaussian-Hermite integration. Applying G-HI [29], $\int_{-\infty}^{\infty} h(z) exp\left(-z^2\right) dz \approx \sum_{i=1}^{L} w_i h\left(z_i\right)$, where, w_i and z_i are weights and abscissas respectively. Assuming $z = \frac{\left(lnv - \mu\right)}{\sqrt{2}\sigma}$ in equation (14), we have

$$f_{\gamma_{MRC}}\left(\gamma\right) = \frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB)\sqrt{\pi}} \int_{-\infty}^{\infty} exp\left(-m\left[B\left(\mu + \sqrt{2}\sigma z\right) + \gamma exp\left(-\left(\mu + \sqrt{2}\sigma z\right)\right)\right]\right) exp\left(-z^2\right) dz \quad (15)$$

Applying G-HI in equation (15); so, the PDF of composite NL fading with MRC diversity is written in equation (16) as

$$f_{\gamma_{mrc}}(\gamma) \approx \frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB)\sqrt{\pi}}\sum_{i=1}^{I} w_i\, exp\left(-m\left[B\left(\mu+\sqrt{2}\sigma z_i\right)+\gamma\, exp\left(-\left(\mu+\sqrt{2}\sigma z_i\right)\right)\right]\right)$$
$$= \frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB)\sqrt{\pi}}\sum_{i=1}^{I} w_i a_i\, exp\left(-b_i\gamma\right) \qquad (16)$$

where, $a_i = exp\left(-mB\left(\mu+\sqrt{2}\,\sigma z_i\right)\right)$,

$b_i = m\, exp\left(-\left(\mu+\sqrt{2}\,\sigma z_i\right)\right)$

III. AVERAGE PROBABILITY OF DETECTION

Once experiencing a composite fading channel, P_F in equation (3) will remain, be the same, since it does not dependent on the SNR. But, when channel gain (g) varies the average probability of detection ($\overline{P_D}$) can be easily evaluated by averaging probability of detection (P_D) in equation (4) over the SNR distribution as [7]

$$\overline{P_D}(\lambda_{th}) = \int_0^{\infty} P_D(\gamma, \lambda_{th}) f_{\gamma_{mrc}}(\gamma)\, d\gamma = \int_0^{\infty} Q_d\left(\sqrt{2\gamma}, \sqrt{\lambda_{th}}\right) f_{\gamma_{mrc}}(\gamma)\, d\gamma \qquad (17)$$

Substituting value of equations (8) and (16) into equation (17), then the $\overline{P_D}$ becomes as

$$\overline{P_D}(\lambda_{th}) = \int_0^{\infty}\sum_{k=0}^{\infty}\frac{\gamma^k}{k!}\frac{\Gamma(d+k, \lambda_{th}/2)}{\Gamma(d+k)} exp(-\gamma)\frac{m^{mB}\gamma^{mB-1}}{\Gamma(mB)\sqrt{\pi}}\sum_{i=1}^{I} w_i a_i\, exp(-b_i\gamma)\, d\gamma \qquad (18)$$

After some mathematical manipulation and using $\int_0^{\infty} z^n exp(-\beta z)\, dz = n!\beta^{-n-1}; \mathrm{Re}\,\beta > 0$ in equation (18), we have $\overline{P_D}$ as shown in equation (19) as

$$\overline{P_D}(\lambda_{th}) = \frac{m^{mB}}{\Gamma(mB)\sqrt{\pi}}\sum_{k=0}^{\infty}\sum_{i=1}^{I}\frac{\Gamma(d+k, \lambda_{th}/2)}{k!\,\Gamma(d+k)} w_i a_i\left((k+mB-1)!\right)(1+b_i)^{-(k+mB)} \qquad (19)$$

IV. THRESHOLD OPTIMIZATION

To determining detection threshold parameter is crucial for accurate estimation of the available band or sub-band of the spectrum. If threshold is too small, it gives an overestimates of the presence of the signal, and thus false alarm would be high resulting in a loss. The problem of optimizing threshold parameter by minimizing the total probability of error for Rayleigh channel is discussed in [19]. The total probability of error (P_{TE}) can be expressed by [17, 19] as

$$P_{TE} = P(H_0)\overline{P_{FA}}(\lambda_{th}) + P(H_1)\overline{P_{MD}}(\lambda_{th}) \qquad (20)$$

Substituting the value of P_{FA} and P_{MD} for MRC diversity, one can frame the expression of the total probability of error. The optimum threshold can be obtained by differentiating total probability of error and be equating it to zero. The total probability of error given by equation (24) has a global minimum with respect to λ_{th}. Hence, we can find optimized value of λ_{th} by minimizing P_{TE} [19] as

$$\lambda_{opt} = arg\, min_{\lambda_{th}}\left(P_{TE}\right) \qquad (21)$$

Considering apriori probability of both the hypothesis to be same, we have

$$\frac{\partial\overline{P_{FA}}(\lambda_{th})}{\partial\lambda_{th}} + \frac{\partial\overline{P_{MD}}(\lambda_{th})}{\partial\lambda_{th}} = 0 \qquad (22)$$

The first term of equation (22) $\partial P_{FA}/\partial\lambda_{th}$ is obtained and the second term

$\partial\overline{P_{MD}}(\lambda_{th})/\partial\lambda_{th} = \partial\left(1-\overline{P_D}(\lambda_{th})\right)/\partial\lambda_{th} = -\partial\overline{P_D}(\lambda_{th})/\partial\lambda_{th}$ is obtained as

$$\frac{\partial\overline{P_D}(\lambda_{th})}{\partial\lambda_{th}} = \frac{m^{mB}}{\Gamma(mB)\sqrt{\pi}}\sum_{k=0}^{\infty}\sum_{i=1}^{I}\frac{w_i a_i}{k!}\left((k+mB-1)!\right)(1+b_i)^{-(k+mB)}\frac{\partial}{\partial\lambda_{th}}\left(\frac{\Gamma(d+k, \lambda_{th}/2)}{\Gamma(d+k)}\right) \qquad (23)$$

After some mathematical calculation, we have $\partial\overline{P_D}/\partial\lambda_{th}$. Now, adding equations (21) and (23) then (22) can be re-written as

$$\lambda_{th} = z\left[\left(\Gamma(d+k)\right)/\left(\frac{m^{mB}\Gamma(d)}{\Gamma(mB)\sqrt{\pi}}\sum_{k=0}^{\infty}\sum_{i=1}^{I}\frac{w_i a_i}{k!}\left((k+mB-1)!\right)(1+b_i)^{-(k+mB)}\right)\right]^{-1/k} \qquad (24)$$

So from equation (21), we get the optimum value of λ_{th} and by using the optimum value of λ_{th}, we can get optimum value of P_{MD}, P_D and P_{TE}.

V. RESULTS

In this section, we extant the complete analysis of the analytical expressions derived in the preceding sections and provide exact numerical results and simulations for validation purpose. In Fig. 2, CROC curves for dual branch diversity are plotted. Three different values of SNR, such as 0 dB, 5 dB and 10 dB are assumed. For low value of SNR, probability of miss-detection is more in comparison to high SNR. Therefore, as the signal-to-noise ratio increases, probability of detection increases and when number of branches are increases, quality of detection of signal improved.

As the number of diversity branches increases in MRC diversity scheme, probability of miss detection is greatly reduced w.r.t the probability of false alarm as shown in Fig. 3. When no diversity case is applied, i.e. SISO then curves approximately overlapping to each other at different fading parameters but when number of diversity branches increases, probability of detection is improved. At higher fading parameter, probability of miss detection is more in comparison to the low fading parameter.

In Fig. 4, complementary ROC curve is plotted for different values of number of sample at different fading parameter values. It is very much clear from the figure that as the number sample size increases, probability of miss-detection reduces that shows the improvement in the detection of the unknown deterministic signal.

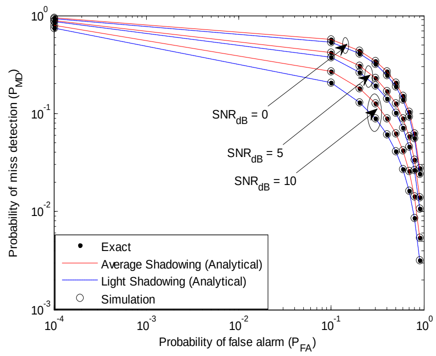

Fig. 2 Complementary ROC curves for light and average shadowing

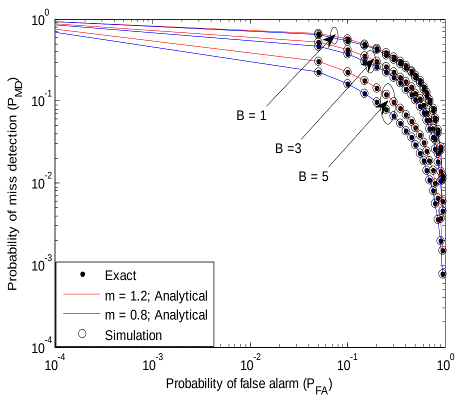

Fig. 3 Complementary ROC curves without and with diversity branches

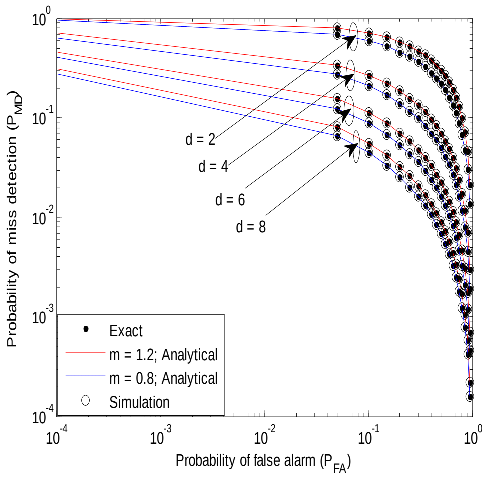

Fig. 4 CROC curves for different d with no diversity (m = 0.8, 1.2, SNR = 0 dB)

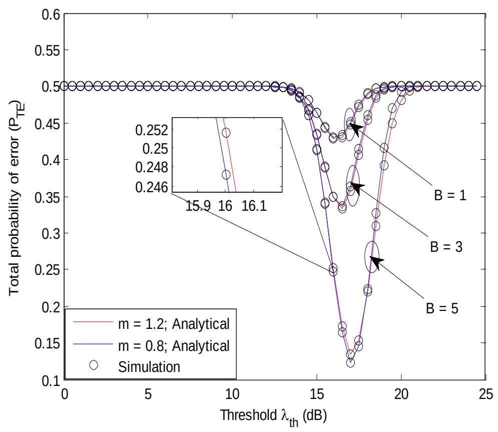

Fig. 5 Total probability of error verses threshold for number of diversity branches

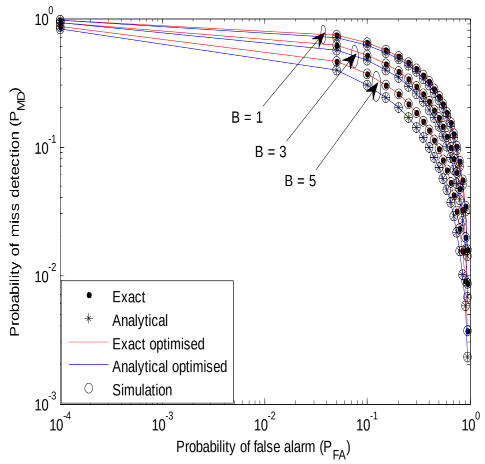

Fig. 6 CROC curves with fixed and optimized threshold for different branches

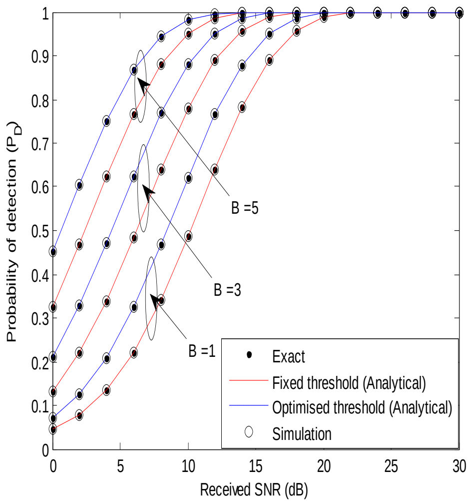

Fig. 7 Probability of detection against received SNR with fixed and optimized threshold

The threshold optimization has been considered in Fig. 5. The inverted bell shaped has been displayed at different number of diversity branches with different fading parameter as obtained. It is observed that the total probability of error (P_{TE}) has global minima w.r.t threshold. The total probability of error decreases as the number of diversity branches increases but when no diversity case is considered, not enough improvement has been shown in the figure.

Fig. 6 illustrate the best response in terms of threshold optimization because in this figure their comparison between fixed threshold and optimized threshold for different number of diversity branches. When no diversity case is considered, not enough deviation in CROC curve for fixed and threshold optimization but still there is small change in optimized threshold. But when the number of diversity branches increases, a great improvement has been seen from the figure. The probability of detection increases, when optimized threshold is applied in comparison to the fixed threshold as the number of diversity branches increases.

In Fig. 7, the probability of detection is shown as a function of received SNR for different number of diversity branches and with fixed and optimized threshold. As the number of diversity branches and received SNR increases, probability of detection converges towards unity. For no diversity case, probability of detection is very small at lower values of SNR but in case of MRC diversity branches, performance of detection shows great improvement as SNR increases.

VI. CONCLUSION

In this paper, we have presented an analytical expression of the average probability of detection with maximum ratio combining over composite NL fading channels using a very simple mathematical tool, Gaussian-Hetmite integration. Additionaly, we have enhanced the threshold parameter by minimizing the total probability of error with respect to threshold. After applying the optimized threshold parameter, a significant improvement in the probability of detection has been demonstrated even at very low SNR. Hence, the performance of optimized threshold is better than the fixed threshold.

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