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Performance Analysis of Energy Detector Over $\alpha - \mu$ Fading Channels with Selection Combining

Hikmat Y. Darawsheh · Ali Jamoos

Abstract Energy detection is the most widely used technique in cognitive radio networks to enable opportunistic spectrum access. In this paper, the problem of energy detection of an unknown deterministic signal over fading channels is revisited. More particularly, a new closed-form mathematical expression is derived for the average probability of detection of the energy detector (ED) over $\alpha - \mu$ generalized fading channels with selection combining (SC) diversity reception. The derived expression is general and includes as special cases Nakagami-*m*, Weibull, Gamma, Rayleigh and Exponential distributions. This expression is useful to quantify the performance improvement of the ED with SC diversity reception.

Keywords Cognitive radio networks · Energy detection · Selection combining · Diversity reception · Fading channels · $\alpha - \mu$ generalized fading distribution

1 Introduction

The static spectrum assignment policy adopted by traditional wireless networks is faced with spectrum scarcity at particular spectrum bands. In addition, a large portion of the assigned spectrum is still under-utilized. To solve these spectrum inefficiency problems, cognitive radio (CR) technology is recently proposed [1]. CR is an intelligent communication system that is aware of its environment. It can sense and adapt its parameters to avoid interference on licensed users. This makes spectrum sensing an important requirement for the realization of CR networks. There are several spectrum sensing techniques proposed in the literature such as energy detection, matched filter detection and feature detection [2]. The ultimate goal of these techniques is to provide more spectrum access opportunities to CR users without causing harmful interference to the primary users. Among the existing spectrum sensing

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techniques, the energy detector (ED) proposed in [3] has the advantage of low cost and simple implementation. It simply measures the received energy on a primary band during an observation interval and declares either a white space if the measured energy is less than a properly set threshold, or occupied if the energy is larger than the threshold.

Several fading distributions have been proposed in the literature to describe the statistics of the mobile radio signal [4]. Indeed, the short-term signal variation is well described by several main distributions such as Nakagami-m, Rayleigh, Rice, Weibull, Hoyt and others. Each of these fading distributions is suitable for certain channel conditions. In some situations, no distributions adequately fit experimental data, although one or another may yield a moderate fitting. This motivates the need for a general fading distribution that can yield better fitting to experimental data and can include several fading distributions as special cases. One of these general fading distributions is the $\alpha - \mu$ distribution recently proposed in [5]. It is an umbrella distribution and includes as special cases important distributions such as Nakagami-m, Rayleigh, Gamma, exponential, Weibull, and one-sided Gaussian. In addition, its probability density function, cumulative distribution function, and moments appear in simple closed form expressions. Furthermore, it can explore the nonlinearity of the propagation medium. These features make the $\alpha - \mu$ distribution very attractive.

Fading channels can extremely affect the transmitted signals resulting in degrading the received signal-to-noise power ratio (SNR). In this case, antenna diversity reception techniques that combine the outputs of multiple fading branches can be used to enhance the SNR at the receiver. Equal gain combining (EGC), maximal ratio combining (MRC), and selection combining (SC) are the most widely used diversity combining techniques [4].

During the last decade, a great deal of interest has been paid to the problem of detecting unknown deterministic signals over a variety of fading channel distributions with or without diversity reception at the receiver [6–8]. Indeed, in [6] the average detection probability performance of ED is derived for Rayleigh, Rician and Nakagami-m fading channels. An alternative analytical approach have been proposed by Digham et al. [7], where closed-form expressions are obtained for the average detection probability over Rayleigh and Nakagami-m fading channels with square-law combining and square-law selection diversity schemes. In [8], the moment generating function (MGF) method and the probability density function (PDF) method are used to evaluate the performance of ED over Rician and Nakagami-m fading models with several diversity combining techniques. However, this yields a wide collection of performance expressions that are applicable only for certain fading models with specific model parameters. To avoid this drawback, Fathi and Tawfik [9] have recently proposed a versatile performance expression for ED over the $\alpha - \mu$ generalized fading channels. Nevertheless, no diversity combining techniques are considered.

In this paper, we propose to extend the results in [9] by considering SC diversity reception at the receiver. A new closed-form expression is derived for the average detection probability of the ED over $\alpha - \mu$ generalized fading channels with SC diversity reception.

The rest of the paper is organized as follows. Section 2 introduces the ED over $\alpha - \mu$ fading channels. Section 3 presents the performance of the ED with SC diversity reception. Numerical results are discussed in Sect. 4. The conclusions are reported in Sect. 5. Finally, the derivation of the new expression is given in "Appendix".

2 Energy Detection Over $\alpha - \mu$ Fading

The ED is a threshold-based decision device. Its output is one of two hypotheses H_0 and H_1 denoting, respectively, signal absence and signal presence. The decision is made by

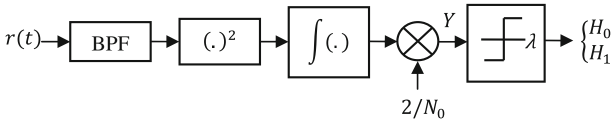

Fig. 1 Block diagram of the energy detector

comparing the aggregated energy of a band-pass-filtered (BPF) received signal, over an observation period of time T s, against a predetermined detection threshold λ as shown in Fig. 1.

Thus, the received signal $r(t)$ can be interpreted as a binary hypothesis test:

$$r\left(t\right)=\begin{cases}n\left(t\right) & H_0\\ h\,s\left(t\right)+n\left(t\right) & H_1\end{cases} \tag{1}$$

where $n(t)$ is an additive white Gaussian noise (AWGN) process with one-sided power spectral density N_0 Watt/Hz, $s\left(t\right)$ is the transmitted signal, and h is the channel coefficient amplitude having mean-square value of $\bar{h}^2$ and PDF $f_h\left(h\right)$. The instantaneous signal-to-noise ratio (SNR) at the receiver antenna can be expressed as $\gamma = |h|^2 E_s/N_0$, where E_s is the energy of the signal accumulated over the observation period. It is well known that the PDF of the decision variable Y can be expressed in terms of the central and non-central Chi-square distributions with $u = TW/2$ degrees of freedom, where W is the BPF bandwidth and TW is the time-bandwidth product. Based on the statistics of Y and given a fixed threshold λ, the conditional probabilities of false alarm $P_f = Pr\left(Y > \lambda|H_0\right)$ and detection $P_d = \Pr\left(Y > \lambda|H_1\right)$ for a certain value of γ can be expressed as [7]:

$$P_f = \frac{\Gamma\left(u, \frac{\lambda}{2}\right)}{\Gamma\left(u\right)} \tag{2}$$

$$P_d = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{3}$$

where $\Gamma(\cdot)$ is the Gamma function, $\Gamma\left(\cdot,\cdot\right)$ is the upper incomplete Gamma function, and $Q_u(\cdot,\cdot)$ is the generalized Marcum Q-function [4, eq.(4.59)].

When the fading channel is characterized by the $\alpha-\mu$ generalized fading distribution, the envelope h of the fading signal has the following PDF $f_h(h)$ [5, eq.(1)]:

$$f_h\left(h\right) = \frac{\alpha\mu^{\mu}h^{\alpha\mu-1}}{\bar{h}^{\alpha\mu}\Gamma\left(\mu\right)}e^{-\mu\left(\frac{h}{\bar{h}}\right)^{\alpha}} \tag{4}$$

where α is a positive arbitrary parameter, and $\mu > 0$ is the inverse of the normalized variance of h^{α}, $\bar{h} = \sqrt[\alpha]{E(h^{\alpha})}$ is the α-root mean value of h, and $\Gamma\left(\mu\right)$ is the Gamma function. By setting $\alpha = K$ and $\mu = 1$, the $\alpha-\mu$ distribution reduces to the Weibull distribution with parameter K. Setting $K = 1$ results in exponential distribution. In addition, Nakagami-m distribution can be obtained by setting $\alpha = 2$ and $\mu = m$, where m is Nakagami-m severity parameter. Furthermore, Rayleigh and one-sided Gaussian distributions are obtained from the Nakagami-m distribution by setting $m = 1$ and $m = 1/2$, respectively. Moreover, Gamma distribution is obtained by setting $\alpha = 1$ and $\mu = a$, where a is the parameter of Gamma distribution. Figures 2 and 3 shows the PDF $f_x\left(x\right)$ of the normalized envelope $x = h/\bar{h}$ of the $\alpha-\mu$ general fading distribution for several values of α and μ, resulting in several well known fading distributions. Indeed, the $\alpha-\mu$ distribution is general, flexible and covers vast range of fading situations [5].

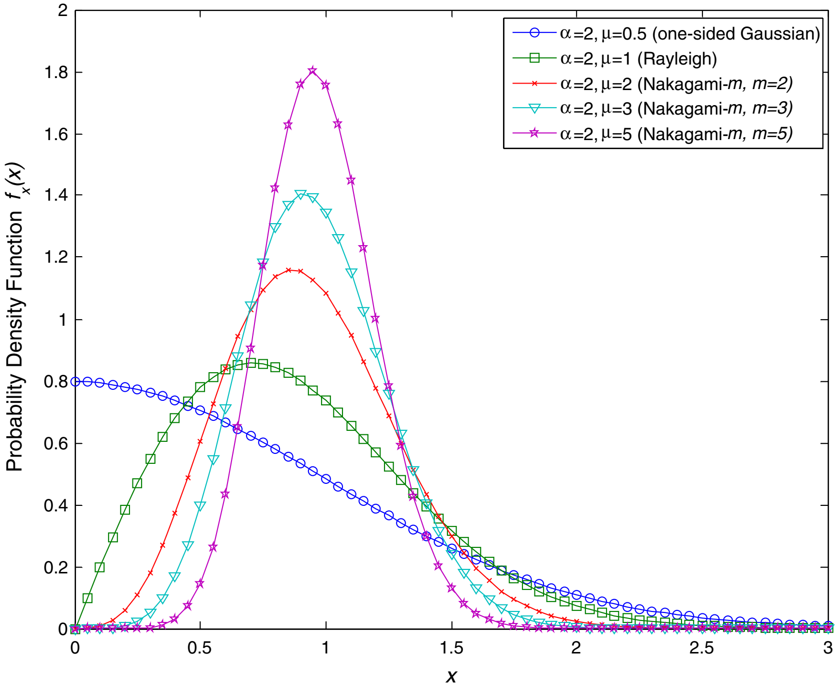

Fig. 2 The probability density function $f_X(x)$ of the $\alpha - \mu$ generalized fading distribution for $\alpha = 2$ with several values of μ

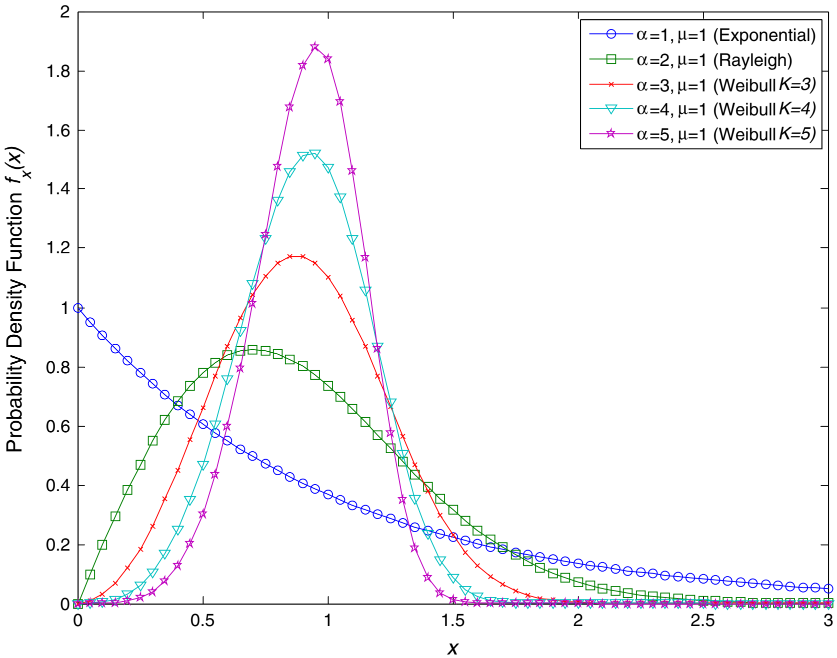

Fig. 3 The probability density function $f_X(x)$ of the $\alpha - \mu$ generalized fading distribution for $\mu = 1$ with several values of α

To obtain the average probability of detection $\bar{P}_d$ when considering AWGN and $\alpha - \mu$ fading channel, Eq. (3) should be averaged over the PDF $f_\gamma(\gamma)$ of the output SNR $\gamma = |h|^2 E_s/N_0$ as follows:

$$\bar{P}_d = \int_0^\infty P_d(\gamma) f_\gamma(\gamma)\, d\gamma \tag{5}$$

where $f_\gamma(\gamma)$ is derived from $f_h(h)$ by simple change of variables as shown in [4, eq.(2.3)]:

$$f_\gamma(\gamma) = \frac{\alpha \mu^\mu \gamma^{\frac{\alpha\mu}{2}-1}}{2\Gamma(\mu)\,\bar{\gamma}^{\frac{\alpha\mu}{2}}} e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}} \tag{6}$$

where $\bar{\gamma} = \bar{h}^2 E_s/N_0$ is the average SNR.

Note that the probability of false alarm given by (2) has no terms relating to fading channel parameters, and so, doesn't change.

3 Performance of Energy Detector with Selection Combining

In [9], the average probability of detection for the ED is obtained over the $\alpha-\mu$ general fading distribution. However, no diversity combining techniques are considered. In this section, the performance of the ED over the $\alpha - \mu$ fading channel is revisited to derive a mathematical expression for the average probability of detection when SC diversity technique is employed at the receiver. When considering SC diversity technique, the diversity branch with highest SNR is chosen by the selection combiner. The PDF of the instantaneous SNR for single branch $\alpha - \mu$ fading channel is given by (6). For L diversity branches, the instantaneous SNR of the SC would be equal to the maximum of $\{\gamma_1, \gamma_2, \ldots, \gamma_L\}$, where γ_i is the ith branch instantaneous SNR. Assuming that the average SNRs for all branches are equal, let's denote it by $\bar{\gamma}$, then for any single branch, the probability that its SNR γ_i is less than some value γ is given by the following cumulative distribution function (CDF) [10]:

$$CDF(\gamma_i) = Pr(\gamma_i \le \gamma) = \int_0^\gamma f_{\gamma_i}(\gamma_i)\, d\gamma_i = \int_0^\gamma \frac{\alpha \mu^\mu \gamma_i^{\frac{\alpha\mu}{2}-1}}{2\Gamma(\mu)\,\bar{\gamma}^{\frac{\alpha\mu}{2}}} e^{-\mu\left(\frac{\gamma_i}{\bar{\gamma}}\right)^{\alpha/2}} d\gamma_i = 1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)} \tag{7}$$

Thus, the CDF of the output SNR of L independent and identically distributed (i.i.d) selection combiner branches can be derived as follows:

$$CDF(\gamma) = Pr(\gamma_1 \le \gamma, \gamma_2 \le \gamma, \ldots, \gamma_L \le \gamma) = \prod_{i=1}^{L} \left(1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right) = \left(1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^L \tag{8}$$

By carrying-out similar steps to those leading to [11, eq. (4)], the PDF of the combiner's output SNR, denoted by $f_{SC}(\gamma)$, can be obtained by differentiating the $CDF(\gamma)$:

$$f_{SC}(\gamma) = \frac{d\,CDF(\gamma)}{d\gamma} = \frac{L\alpha\mu^{\mu}}{2\Gamma(\mu)\,\bar{\gamma}^{\frac{\alpha\mu}{2}}} \left(1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^{L-1} \gamma^{\frac{\alpha\mu}{2}-1} e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}} \tag{9}$$

Therefore, the average probability of detection for the SC can be evaluated by averaging (3) over (9) as follows:

$$\bar{P}_{d,\alpha\mu,sc} = \int_0^{\infty} Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \times \frac{L\alpha\mu^{\mu}}{2\Gamma(\mu)\,\bar{\gamma}^{\frac{\alpha\mu}{2}}} \left(1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^{L-1} \gamma^{\frac{\alpha\mu}{2}-1} e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}} d\gamma \tag{10}$$

Following the derivation in "Appendix", the average probability of detection of the ED over $\alpha - \mu$ generalized fading channels with SC diversity reception can be expressed as:

$$\bar{P}_{d,\alpha\mu,sc} = C \sum_{n=0}^{\infty} a_n \sum_{i=0}^{L-1} (-1)^i \binom{L-1}{i} \sum_{m=0}^{i(\mu-1)} \frac{\mu^m l^{\frac{\alpha m}{2}+n}}{\bar{\gamma}^{\frac{\alpha m}{2}}} \beta_{mi}(\mu) G_{l,k}^{k,l}\left(z;\, \begin{matrix} \Delta(l, -w) \\ \Delta(k, 0) \end{matrix}\right) \tag{11}$$

where $C = \frac{\alpha\mu^{\mu} L\sqrt{k} l^{\frac{1}{2}(\alpha\mu-1)}}{2\Gamma(\mu)\bar{\gamma}^{\frac{1}{2}(\alpha\mu)}(2\pi)^{\frac{k+l}{2}-1}}$, $a_n = \frac{\Gamma\left(n+u, \frac{\lambda}{2}\right)}{n!\Gamma(n+u)}$, $z = l^l\left(\frac{(i+1)\mu}{k\bar{\gamma}^{\alpha/2}}\right)^k$, and $w = \frac{1}{2}\alpha(\mu + m) + n - 1$. In addition, $G_{p,q}^{q,p}\left(z;\, \begin{matrix} a_1, \ldots, a_p \\ b_1, \ldots, b_q \end{matrix}\right)$ is the Meiger-G function [13, eq.(16.17.1)], $\Delta(k, a) = \frac{a}{k}, \frac{a+1}{k}, \ldots, \frac{a+k-1}{k}$, l and k are some integers such that $\frac{l}{k} = \frac{\alpha}{2}$, $\beta_{mi}(\mu)$ is the multinomial expansion coefficient which can be computed recursively as illustrated in [4, eq.(9.124)]. To the best of authors' knowledge, (11) is new.

In the case of no diversity reception, i.e. single diversity branch $L = 1$, the derived expression for the probability of detection of the ED with SC diversity reception in (11) reduces to a previously known result found in [9, eq.(8)], as follows:

$$\bar{P}_d = A \sum_{n=0}^{\infty} l^n a_n G_{l,k}^{k,l}\left(S;\, \begin{matrix} \Delta(l, -v) \\ \Delta(k, 0) \end{matrix}\right) \tag{12}$$

where $A = \frac{\alpha\mu^{\mu}\sqrt{k} l^{(\alpha\mu-1)/2}}{2\Gamma(\mu)\bar{\gamma}^{\left(\frac{\alpha\mu}{2}\right)}(2\pi)^{\frac{k+l}{2}-1}}$, $S = \left(\frac{\mu}{k\bar{\gamma}^{\alpha/2}}\right)^k l^l$, and $v = n + \frac{\alpha\mu}{2} - 1$. Note that a typo in [9, eq.(8)] is fixed in (12) by adding the missing term l^n.

For the special case of Rayleigh fading channels, the probability of detection for the ED with SC diversity reception can be found from (11) by setting $\alpha = 2$ and $\mu = 1$:

$$\bar{P}_{d,Ray,SC,L} = \frac{L}{\bar{\gamma}} \sum_{n=0}^{\infty} \frac{\Gamma\left(n+u, \frac{\lambda}{2}\right)}{\Gamma(n+u)} \sum_{i=0}^{L-1} (-1)^i \left(\frac{\bar{\gamma}}{1+i+\bar{\gamma}}\right)^{n+1} \binom{L-1}{i} \tag{13}$$

It should be noted that (13) is an alternative form to the one derived in [14, eq.(30)]. For the no diversity case $L = 1$, Eq. (13) reduces to:

$$\bar{P}_{d,Ray,L=1} = \frac{1}{1+\bar{\gamma}} \sum_{n=0}^{\infty} \frac{\Gamma\left(n+u, \frac{\lambda}{2}\right)}{\Gamma(n+u)} \left(\frac{\bar{\gamma}}{1+\bar{\gamma}}\right)^n \tag{14}$$

4 Numerical Results and Discussion

In this section, the performance of the ED is quantified by depicting the Receiver Operating Characteristics (ROC) ($\bar{P}_d$ vs. P_f), or equivalently, complementary ROC (probability of miss detection $P_m = 1 - \bar{P}_d$ vs. P_f) for different values of the environment nonlinearity parameter α, number of multipath clusters μ, and number of SC diversity branches L. In the following examples, the degree of freedom u of both H_0 and H_1 distributions are set to $u = 5$.

Figure 4 shows the complementary ROC of the ED over $\alpha - \mu$ fading channel with different values of α when $L = 1, 3$. One can notice that the performance of the ED is greatly improved when increasing the number of SC diversity branches from $L = 1$ to $L = 3$. For example, when $\alpha = 2$ and $P_f = 0.1$ the probability of miss detection is decreased from 0.2 to 0.04 when increasing the number of SC diversity branches from L =1 to L =3. Thus, SC diversity reception can greatly improve the probability of detection of the ED. In addition, increasing the value of the nonlinearity parameter α improves the performance of the ED by decreasing the probability of miss detection. Indeed, increasing α enhances the tail under the PDF as illustrated in Fig. 3, and hence for a given fixed threshold it decreases the miss detection probability.

According to Fig. 5, the complementary ROC of the ED is greatly enhanced when L is increased from $L = 1$ to $L = 3$ with the several values of μ. For example, when $\mu = 2$ and $P_f = 0.3$ the probability of miss detection is decreased from 0.1 to 0.015 when increasing the number of SC diversity branches from $L = 1$ to $L = 3$. In addition, increasing the value of μ increases the number of multipath clusters contributing to the envelope of the received signal, and hence increases the diversity gain resulting in lower miss detection probability.

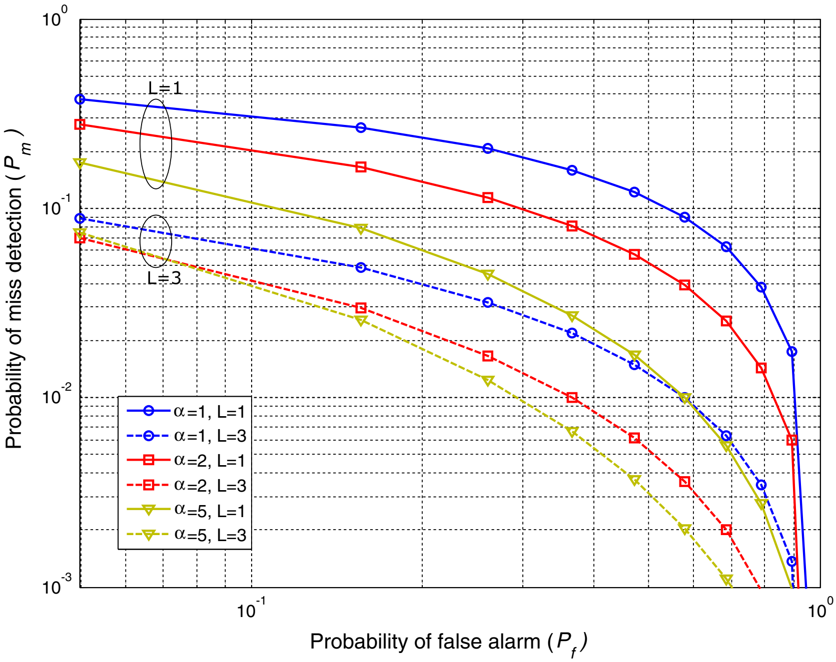

Fig. 4 Complementary ROC curves of the ED for $\alpha - \mu$ fading channel with SC and different values of α. $\mu = 2$ and $\bar{\gamma} = 10$ dB

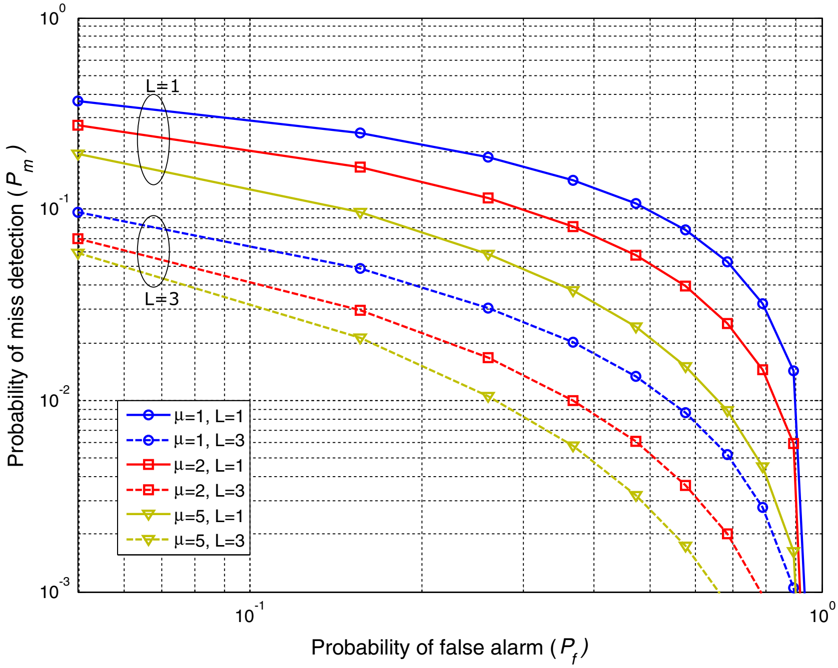

Fig. 5 Complementary ROC curves of the ED for $\alpha - \mu$ fading channel with SC and different values of μ. $\alpha = 2$ and $\bar{\gamma} = 10\,\text{dB}$

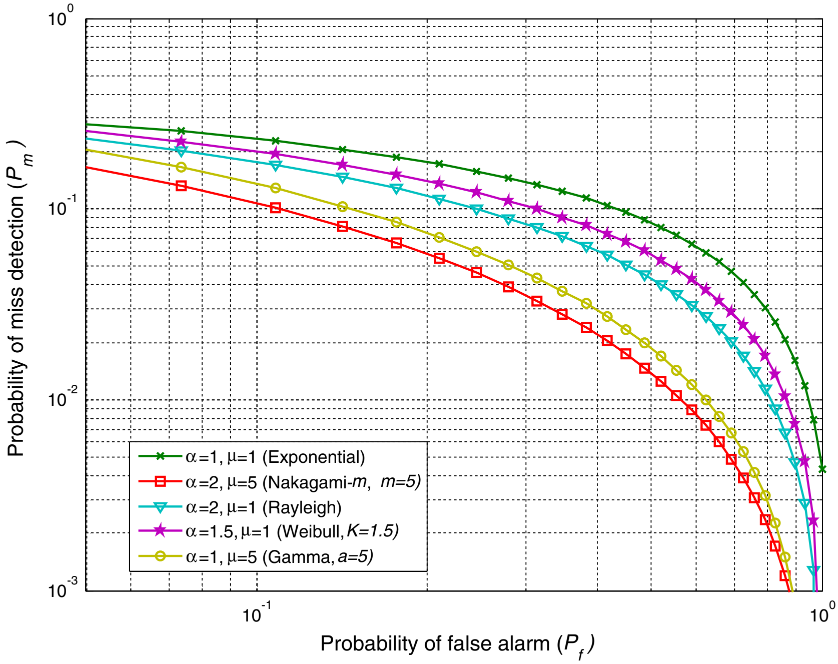

Fig. 6 Complementary ROC curves of the ED over different fading channels with dual SC ($L = 2$). $\bar{\gamma} = 9\,\text{dB}$

Figure 6 shows the complementary ROC of the ED for several well known fading distributions obtained as special cases from the generalized $\alpha - \mu$ fading distribution by selecting different values of fading parameters α and μ. Exponential, Nakagami-m, Rayleigh, Weibull and Gamma fading distributions are special cases of the $\alpha - \mu$ fading distribution. On the one hand, exponentially faded channel yields the worst performance. In that case, lower signal envelope amplitudes occur more frequent than higher ones. Thus, the exponential fading distribution can be used as a performance bound benefiting from its mathematical tractability. On the other hand, increasing the value of the severity parameter m in the Nakagami-m fading distribution improves the performance of the ED by decreasing the probability of miss detection.

5 Conclusion

In this paper, a new closed-form mathematical expression is derived for the probability of detection of the ED over $\alpha - \mu$ generalized fading model with SC diversity reception. The derived expression covers several known fading distribution models as special cases. Complementary ROC curves were drawn for the ED over $\alpha - \mu$ fading channels where enhancement of the probability of detection was achieved by using SC diversity reception.

Appendix: Evaluation of $\bar{P}_{d,\alpha\mu,sc}$

The generalized Marcum Q-function $\mathrm{Q_u}\left(\sqrt{2\Upsilon}, \sqrt{\lambda}\right)$ in (10) can be rewritten into series representation using [4, eq.(4.74)] as follows:

$$Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) = \sum_{n=0}^{\infty} \frac{\Gamma\left(n+u, \frac{\lambda}{2}\right)}{n!\Gamma(n+u)} \gamma^n \mathrm{e}^{-\gamma} \tag{15}$$

In addition, the term $\left(1 - \frac{\Gamma\left(\mu,\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^{L-1}$ in (10) can be simplified into series representation by means of binomial and then multinomial expansions, respectively, as follows:

- *Binomial expansion*

$$\left(1 - \frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^{L-1} = \sum_{i=0}^{L-1} (-1)^i \binom{L-1}{i} \left(\frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)}\right)^i \tag{16}$$

  Using [15, eq. (8.352-4)] with the help of the equality $\Gamma(\mu) = (\mu-1)!$ and taking into consideration integer values only for the μ parameter, it follows that:

$$\frac{\Gamma\left(\mu, \mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)}{\Gamma(\mu)} = e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}} \sum_{m=0}^{\mu-1} \frac{\left(\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)^m}{m!} \tag{17}$$

- *Multinomial expansion*

$$\left(e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}}\sum_{m=0}^{\mu-1}\frac{\left(\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)^{m}}{m!}\right)^{i}=e^{-i\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}}\sum_{m=0}^{i(\mu-1)}\beta_{mi}\left(\mu\right)\left(\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)^{m} \tag{18}$$

where $\beta_{mi}(\mu)$ is the multinomial expansion coefficient which can be computed recursively as illustrated in [4, eq.(9.124)].

Substituting (18) into (16) and then substituting (16) and (15) into (10), the average probability of detection can be expressed as:

$$\bar{P}_{d,\alpha\mu,sc}=\int_{0}^{\infty}\sum_{n=0}^{\infty}\frac{\Gamma\left(n+u,\frac{\lambda}{2}\right)}{n!\Gamma(n+u)}\gamma^{n}e^{-\gamma}\times\frac{L\alpha\mu^{\mu}}{2\Gamma\left(\mu\right)\bar{\gamma}^{\frac{\alpha\mu}{2}}}\sum_{i=0}^{L-1}(-1)^{i}\binom{L-1}{i}e^{-i\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}}$$
$$\times\sum_{m=0}^{i(\mu-1)}\beta_{mi}\left(\mu\right)\left(\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}\right)^{m}\gamma^{\frac{\alpha\mu}{2}-1}e^{-\mu\left(\frac{\gamma}{\bar{\gamma}}\right)^{\alpha/2}}d\gamma \tag{19}$$

Following similar manipulation steps to those leading to [9, eq.(7)], the integral in (19) can be put in the form of Laplace transform. Hence, using [12, 2.2.1-22] the average probability of detection in (11) follows.

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