Energy Detection of Unknown Signals Over Cascaded Fading Channels

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***Abstract*—Energy detection is a favorable mechanism in several applications relating to the identification of deterministic unknown signals such as in radar systems and cognitive radio communications. The present work quantifies the detrimental effects of cascaded multipath fading on energy detection and investigates the corresponding performance capability. A novel analytic solution is first derived for a generic integral that involves a product of the Meijer G-function, the Marcum Q-function, and arbitrary power terms. This solution is subsequently employed in the derivation of an exact closed-form expression for the average probability of detection of unknown signals over $N*$Rayleigh channels. The offered results are also extended to the case of square-law selection, which is a relatively simple and effective diversity method. It is shown that the detection performance is considerably degraded by the number of cascaded channels and that these effects can be effectively mitigated by a nonsubstantial increase of diversity branches.**

***Index Terms*—Cascaded fading, diversity, energy detection.**

I. Introduction

EFFECTIVE detection of unknown signals has been a critical research topic since it is typically encountered in applications relating to RADAR, cognitive radio, and ultrawideband systems. Energy detection (ED) has been the most widely considered detection method due to its noncoherent structure and low implementation complexity; see [1] and the references therein. Its operation is based on the deployment of a radiometer that its output decision is determined by comparing the received energy level with a reference energy threshold. In the context of cognitive radio, this decision indicates the presence or absence of unknown signals, while the overall detection capability has been typically characterized by the corresponding probability of detection, $P_{\rm d}$, and probability of false alarm, $P_{\rm f}$ [1]. Since the objective in such systems is not information recovery, the process is solely based on the amount of its energy regardless of its other parameters, such as carrier phase information. Therefore, in the context of ED, an unknown signal is defined as a deterministic signal with an unknown form, which can be considered a sample function of a random process. However, knowledge of the spectral region to which it is confined along with the estimated signal-to-noise ratio (SNR) statistics are sufficient to allow design of suitable energy detectors [2].

Capitalizing on the fundamental contribution of [1], numerous investigations have been reported on the performance and behavior of ED in various practical scenarios. Specifically, thorough analyses over multipath and composite fading channels were carried out for both single-channel and multichannel scenarios in [2]–[9] and the references therein. In the same context, the performance over hyper Rayleigh conditions was analyzed in [10]. Nevertheless, in spite of the usefulness of the reported analyses, none of them accounts for the case of cascaded fading channels. The detrimental effects in such fading conditions are because transmitted signals are exposed to a product of a large number of rays reflected by N statistically independent scatterers. For example, it is practically demonstrated in [11] that cascaded channels can accurately model the abrupt and rapid fading dynamics resulting from large mobile scatterers in intervehicular communications.

Cascaded fading conditions are also encountered in scenarios such as multihop cooperative communications and multiple-input–multiple-output (MIMO) keyhole communications systems [12]. In multihop relay cognitive radio networks, ED is performed by cooperative sensing, where the process of detecting the primary signal is replicated through a number of multihop sensing nodes by means of nonregenerative relaying. Similarly, in the case of keyhole MIMO channels, a multiantenna secondary user employs ED to sense the spectrum of a multiantenna primary user [13]. Likewise, cognitive vehicular networks (CVNs) have been proposed as an effective method to provide adequate and robust operation in daily road traffic, and thus, vehicular nodes have to be equipped with efficient spectrum sensing capabilities [14].

Motivated by the above, the present work quantifies the behavior and performance of ED under cascaded Rayleigh fading conditions for both single-channel and multichannel scenarios. This topic was partly addressed in [15] by deriving an infinite

Manuscript received February 12, 2015; accepted April 11, 2015. Date of publication May 14, 2015; date of current version February 10, 2016.

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Digital Object Identifier 10.1109/LAWP.2015.2433212

series, which was not studied in terms of accuracy and convergence. On the contrary, in the present analysis, a novel analytic expression is firstly derived for an infinite integral involving a product of a Meijer G-function, a Marcum Q-function, and power terms. This solution is generic and is anticipated to be useful in various analyses relating to natural sciences and engineering. To this end, it is employed in the derivation of an exact closed-form expression for the $\overline{P}_{\rm d}$ of ED over N cascaded Rayleigh channels. The derived expression is subsequently employed in extending the offered results to the case of square-law selection, which is a relatively simple and robust diversity method that exhibits improved performance.

II. Channel and System Model

A. $N{*}$Rayleigh Fading

It is recalled that multiplicative fading models are capable of accounting for fading phenomena holistically [12]. Physically, these models consider received signals generated by the product of a large number of rays reflected via N scatterers [11], [12]. Based on this, a generic cascaded fading model, so called $N{*}$Nakagami–m, was proposed in [12] that is constructed by the product of N statistically independent but not necessarily identically distributed Nakagami–m random variables. When $m = 1$, this model reduces to the $N{*}$Rayleigh distribution with probability density function (PDF)

$$p_\gamma(\gamma) = \frac{1}{\gamma} G_{0,N}^{N,0}\left[\frac{\gamma}{\overline{\gamma}}\left|\begin{matrix} - \\ \underbrace{1,1,\cdots,1}_{N}\end{matrix}\right.\right] \tag{1}$$

where γ and $\overline{\gamma}$ denote the instantaneous and average SNR, respectively, and $G(\cdot)$ is the Meijer G-function. For the special case that $N = 2$, $N{*}$Rayleigh reduces to the double Rayleigh fading model, which has been used to model fading conditions in realistic communication scenarios, including mobile transmitter and receivers [10], [11]. It is also noted that cascaded fading models have been used in modeling the keyhole channel in multiantenna systems [12].

B. Energy Detection of Unknown Signals

The detection of unknown signals can be modeled as a binary hypothesis-testing problem, where H_0 and H_1 correspond to the cases that a signal is absent or present, respectively. Based on this, the received signal can be expressed as [1]

$$y(t) = \begin{cases} n(t) & : H_0 \\ hs(t) + n(t) & : H_1 \end{cases} \tag{2}$$

where h and $s(t)$ denote the wireless channel gain and the transmitted information signal with average power E_s, respectively, and $n(t)$ is the zero-mean complex additive white Gaussian noise (AWGN) with single-sided power spectral density N_0. The received signal is firstly band-pass filtered at bandwidth B (Hz), and the output of the filter is subsequently squared and integrated over time duration T. This generates the test statistic Y, which is typically formulated as [1]

$$Y \sim \begin{cases} \chi_{2u}^2 & : H_0 \\ \chi_{2u}^2(2\gamma) & : H_1 \end{cases} \tag{3}$$

where χ_{2u}^2 is a central chi-square distribution with $2u$ degrees of freedom with u denoting the corresponding time-bandwidth product. Likewise, $\chi_{2u}^2(2\gamma)$ is a noncentral chi-square distribution with the same degrees of freedom and a noncentrality parameter 2γ, with $\gamma = |h|^2 E_s/N_0$ denoting the instantaneous SNR of the target signal. Finally, the test statistic Y is compared to an energy threshold λ, which determines the absence or presence of the signal under test [1]. In the case of AWGN, the probability of false alarm and probability of detection are expressed as $P_{\rm f} = \Pr(Y > \lambda | H_0) = G(u, \lambda/2)$ and $P_{\rm d} = \Pr(Y > \lambda | H_1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda})$, respectively, where $G(a,b)$ and $Q_u(a,b)$ are the regularized upper incomplete gamma function and the Marcum Q-function, respectively.

III. Energy Detection Over $N{*}$Rayleigh Channels

Meijer G- and Marcum Q-functions are particularly important in wireless communications. However, to the best of the authors' knowledge, no tabulated solutions for integrals that involve a product of a Meijer G-function, a Marcum Q-function and arbitrary power terms exist in the literature.

Theorem 1: For $t \in \mathbb{R}$, $u, b, c \in \mathbb{R}^+$, $m, n, p, q \in \mathbb{N}$, and $G(\cdot,\cdot)$ denoting the bivariate Meijer G-function, (5), is valid for the integral

$$\begin{aligned} \mathcal{I} = \int_0^\infty & x^{t-1} Q_u(b\sqrt{x}, c) G_{p,q}^{m,n} \\ & \times \left(kx \left| \begin{matrix} a_1, \cdots, a_n, a_{n+1}, \cdots, a_p \\ b_1, \cdots, b_m, b_{m+1}, \cdots, b_q \end{matrix} \right.\right) {\rm d}x \end{aligned} \tag{4}$$

$$\begin{aligned} \mathcal{I} = & -\frac{2k}{b^2} G_{1,0:1,3:p+1,q+1}^{0,1:1,0:m,n+1} \\ & \times \left(\begin{matrix} 0 \\ - \end{matrix} \left| \begin{matrix} 1/2 \\ 0,-u,1/2 \end{matrix} \right| \begin{matrix} 1,t+a_1,\cdots,t+a_n,t+a_n+1,\cdots,t+a_p \\ t+b_1,\cdots,t+b_m,0,t+b_m+1,\cdots,t+b_q \end{matrix} \left| \frac{c}{2}, \frac{2k}{b^2} \right.\right). \end{aligned} \tag{5}$$

Proof: By setting $y = kx$ in (4), it immediately follows that

$$\mathcal{I} = \int_0^\infty \frac{Q_u\left(\frac{b\sqrt{y}}{\sqrt{k}}, c\right)}{y^{1-t}k^t} G_{p,q}^{m,n}\left(y \left| \begin{matrix} a_1,\cdots,a_n,a_{n+1},\cdots,a_p \\ b_1,\cdots,b_m,b_{m+1},\cdots,b_q \end{matrix}\right.\right) {\rm d}y. \tag{6}$$

The above integral is improper; as a result, by integrating by parts with respect to the power term and the Meijer G-function using [16, Eq. (07.34.21.0002.01)], one obtains

$$\begin{aligned} \mathcal{I} = & \lim_{y\to\infty} \frac{f(y)}{k^t} Q_u\left(\frac{b\sqrt{y}}{\sqrt{k}}, c\right) - \lim_{y\to 0} \frac{f(y)}{k^t} Q_u\left(\frac{b\sqrt{y}}{\sqrt{k}}, c\right) \\ & - \frac{1}{k^t} \int_0^\infty f(y) \left\{ \frac{\rm d}{{\rm d}y} Q_u\left(\frac{b\sqrt{y}}{\sqrt{k}}, c\right)\right\} {\rm d}y \end{aligned} \tag{7}$$

where

$$f(y) = G_{p+1,q+1}^{m,n+1}\left(y \left| \begin{matrix} 1,t+a_1,\cdots,t+a_n,t+a_{n+1},\cdots,t+a_p \\ t+b_1,\cdots,t+b_m,0,t+b_{m+1},\cdots,t+b_q \end{matrix}\right.\right). \tag{8}$$

Evidently, both limits in (7) approach zero, yielding

$$\mathcal{I} = -\frac{1}{k^t} \int_0^\infty f(y) \left\{ \frac{\rm d}{{\rm d}y} Q_u\left(\frac{b\sqrt{y}}{\sqrt{k}}, c\right)\right\} {\rm d}y. \tag{9}$$

The derivative of the Marcum Q-function with respect to y can be determined with the aid of [17]. Hence, by performing the necessary change of variables, substituting in (9) along with (8), and carrying out basic manipulations, it follows that

$$\mathcal{I} = -\int_0^\infty \frac{G_{p+1,q+1}^{m,n+1}\left(y \left| {1,t+a_1,\cdots,t+a_n,t+a_{n+1},\cdots,t+a_p \atop t+b_1,\cdots,t+b_m,0,t+b_{m+1},\cdots,t+b_q} \right.\right)}{2c^{-u}k^{t+1-\frac{u}{2}}b^{u-2}e^{\frac{c^2}{2}}y^{\frac{u}{2}}e^{\frac{yb^2}{2k}}\left[I_u\left(bc\sqrt{\frac{y}{k}}\right)\right]^{-1}}\mathrm{d}y \tag{10}$$

where $I_n(x)$ is the modified Bessel function of the first kind. By then expressing the $\exp(\cdot)$ and $I_n(\cdot)$ functions in terms of the Meijer G-function, the following equation is deduced:

$$\begin{aligned}\mathcal{I} = 1 - &\frac{\pi b^2 c^{2u} e^{-\frac{c^2}{2}}}{2^{u+1}k^{t+1}} \int_0^\infty G_{0,1}^{1,0}\left(\frac{b^2 y}{2k}\left|{- \atop 0}\right.\right)\\ &\times G_{1,3}^{1,0}\left(\frac{b^2c^2y}{4k}\left|{1/2 \atop 0,-u,1/2}\right.\right)\\ &\times G_{p+1,q+1}^{m,n+1}\left(y\left|{1,t+a_1,\cdots,t+a_n,t+a_{n+1},\cdots,t+a_p \atop t+b_1,\cdots,t+b_m,0,t+b_{m+1},\cdots,t+b_q}\right.\right)\mathrm{d}y.\end{aligned} \tag{11}$$

Importantly, this integral can be expressed in closed form with the aid of [16, Eq. (07.34.21.0081.01)]. Thus, performing the necessary change of variables and substituting in (11) yields (5), which completes the proof. □

Remark 1: The Meijer G-function of one and two variables is used increasingly in wireless communications and can be evaluated numerically with the aid of the algorithm in [18, Table II]. It is also algebraically related to the respective Fox H-functions, and thus (5) can be also generically represented in terms of the Fox H-function for the special case that $\mathcal{C} = 1$.

A. Average Probability of Detection in N∗Rayleigh Fading

As already mentioned, the generic solution in (5) can be used in numerous applications in wireless communications.

Corollary 1: For $u, \lambda, \overline{\gamma} \in \mathbb{R}^+$ and $N \in \mathbb{N}$, the following equation holds for the average probability of detection over N∗Rayleigh fading channels with $G^{-1}(\cdot,\cdot)$ denoting the inverse regularized incomplete gamma function:

$$\begin{aligned}\overline{P}_\mathrm{d} = &G_{2,1:1,3:1,N+1}^{0,1:1,0:N,1}\\ &\times\left(\begin{matrix}\frac{u}{2},\frac{u-1}{2}\\ \frac{u-1}{2}\end{matrix}\left|\begin{matrix}\frac{1}{2}\\ 0,-u,\frac{1}{2}\end{matrix}\right|\begin{matrix}1\\ 1,\cdots,1,0,1\end{matrix}\left|-G^{-1}(u,P_\mathrm{f}),-\frac{1}{\overline{\gamma}}\right.\right).\end{aligned} \tag{12}$$

Proof: It is recalled that $\overline{P}_\mathrm{d}$ is obtained by averaging P_d over the statistics of the corresponding fading channel, namely [1]

$$\overline{P}_\mathrm{d} = \int_0^\infty Q_u(\sqrt{2\gamma},\sqrt{\lambda})p_\gamma(\gamma)\mathrm{d}\gamma \tag{13}$$

$$= \int_0^\infty Q_u\left(\sqrt{2\gamma},\sqrt{2G^{-1}(u,P_\mathrm{f})}\right)p_\gamma(\gamma)\mathrm{d}\gamma. \tag{14}$$

To this effect, by substituting (1) in (13), it follows that

$$\overline{P}_\mathrm{d} = \int_0^\infty \frac{1}{\gamma}Q_u(\sqrt{2\gamma},\sqrt{\lambda})G_{0,N}^{N,0}\left[\frac{\gamma}{\overline{\gamma}}\left|{- \atop \underbrace{1,1,\cdots,1}_{N}}\right.\right]\mathrm{d}\gamma. \tag{15}$$

The above expression can be evaluated using Theorem 1 since the involved integral is a special case of (4). Hence, performing the necessary variable transformation in (5) and substituting in (15) yields (12), which completes the proof. □

B. Square-Law Selection (SLS)

Square-law selection is an effective and relatively simple diversity method [1]. Its operation is based on selecting the branch, among L branches, with the maximum decision statistic, $y_\mathrm{SLS} = \max(y_1,\cdots,y_L)$. For ED over fading channels, the corresponding average probability of detection is given by

$$\overline{P}_{d,\mathrm{SLS}} \triangleq 1 - \prod_{i=1}^{L}\{1-\overline{P}_\mathrm{d}(\overline{\gamma}_i)\}. \tag{16}$$

Corollary 2: For $u, \lambda, \overline{\gamma} \in \mathbb{R}^+$ and $N \in \mathbb{N}$, the average probability of detection over N∗Rayleigh channels with square-law selection is given by

$$\begin{aligned}\overline{P}_{d,\mathrm{SLS}} = 1 - \prod_{i=1}^{L}&\left\{1 - G_{2,1:1,3:1,N+1}^{0,1:1,0:N,1}\right.\\ &\left.\times\left(\begin{matrix}\frac{u}{2},\frac{u-1}{2}\\ \frac{u-1}{2}\end{matrix}\left|\begin{matrix}\frac{1}{2}\\ 0,-u,\frac{1}{2}\end{matrix}\right|\begin{matrix}1\\ 1,\cdots,1,0,1\end{matrix}\left|-\frac{\lambda}{2},-\frac{1}{\overline{\gamma}_i}\right.\right)\right\}.\end{aligned} \tag{17}$$

Proof: The proof follows by substituting (12) into (16).

IV. Numerical Results

The offered results are used in analyzing the behavior and performance of ED-based spectrum sensing over N∗Rayleigh fading channels for single-channel and multichannel cases. This enables us to quantify the corresponding detrimental effects and propose simple and efficient compensation methods.

Fig. 1 demonstrates the average probability of detection as a function of the average SNR for different values of N and L and for $u = 5$ and $P_\mathrm{f} = 0.1$, which is considered realistic for most practical applications, such as spectrum sensing. The value of $\overline{P}_\mathrm{d}$ is shown to reduce considerably as the number of cascaded channels increases. For example, for $\overline{\gamma} = 15$ dB, the $\overline{P}_\mathrm{d}$ deviation between $N = 1$ and $N = 3$ is 31%, whereas that between $N = 3$ and $N = 5$ for $\overline{\gamma} = 20$ dB is 28%. These cases correspond to deviations that render the ED capability inadequate since the achieved $\overline{P}_\mathrm{d}$ is practically low even at the high SNR regime. However, it is noticed that employing SLS provides considerable performance compensation even for a small number of diversity branches. Indicatively, it is shown that when $N = 5$, the $\overline{P}_\mathrm{d}$ increases substantially for any extra added branch L. This is also illustrated in the receiver operating characteristics (ROC) curve in Fig. 2, where the value of $\overline{P}_m$ for $N = 5$ and $L = 3$ is comparable to that for $N = 1$ and $L = 1$. As a result, the detector appears to perform better when $L \geq 4$ than in the respective single Rayleigh fading scenario. Furthermore, the overall performance benefits of SLS are more notable in the moderate and low SNR regimes where the single channel scenario performs quite poorly.

Finally, unlike the single-channel case where increasing N degrades the performance substantially, a slight degradation is observed as N increases when adopting SLS. Overall, in both

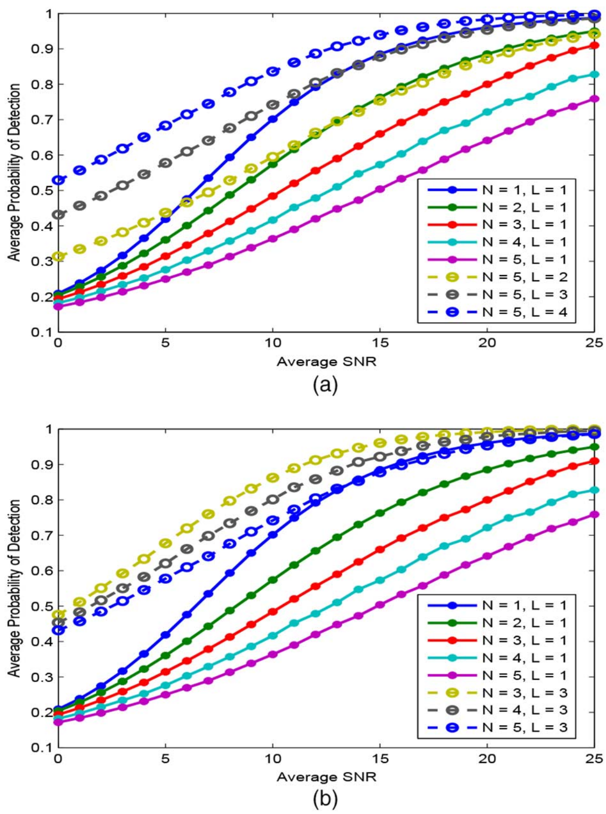

Fig. 1. (a), (b) $\overline{P}_{\rm d}$ versus $\overline{\gamma}$ for different N and L with $u = 5$ and $P_{\rm f} = 0.1$.

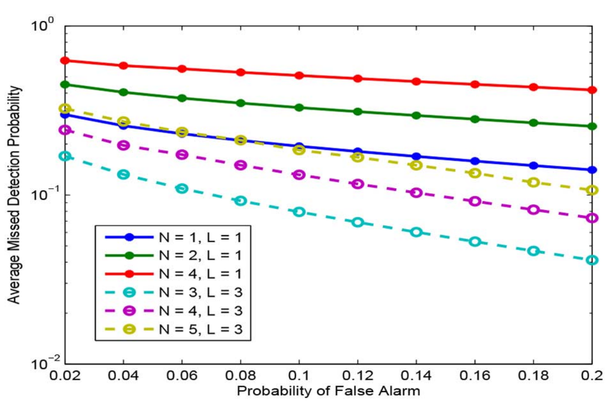

Fig. 2. ROC curve for different N and L with $u = 4$ and $\overline{\gamma} = 12$ dB.

low and high average SNR values, it is observed that considering in practice a three-branch SLS receiver can sufficiently overcome the severe degradation by cascaded fading effects.

V. Conclusion

This letter quantified the effects of cascaded fading on energy detection. A generic analytic solution was first derived for an integral that involves a product of a Marcum Q-function, a Meijer G-function, and a power term. This solution was subsequently employed in the derivation of closed-form expressions for the average probability of detection over N cascaded Rayleigh fading channels, which was then extended to the case of square-law selection. It was shown that the involved number of cascaded channels affect considerably the achieved performance. However, the corresponding degradation can be effectively compensated with the aid of square-law selection as it was shown that three or more branches are sufficient for achieving comparable or better performance than conventional detection over Rayleigh fading conditions.

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