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On the performance analysis of wireless receiver using generalized-gamma fading model

Jyoteesh Malhotra · Ajay K. Sharma · R. S. Kaler

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Abstract In this paper, we provide a unified analysis for wireless system over generalized fading channels that is modeled by the two parameter generalized gamma model. This model is versatile enough to represent short-term fading such as Weibull, Nakagami-m, or Rayleigh as well as shadowing. The performance measures such as the amount of fading, average bit error rate, and signal outage are considered for analysis. With the aid of moment generating function (MGF) approach and Padé approximation (PA) technique, outage probability and average bit error rate have been evaluated for a variety of modulation formats. We first use the PA technique to find a simple way to evaluate compact rational expressions for the MGF of output signal-to-noise ratio, unlike previously derived intricate expressions in terms of Fox's H and MeijerG functions. Using these rational expressions, we evaluate the performance of wireless receivers under a range of representative channel fading conditions. Our results are validated through computer simulations, which shows perfect match.

J. Malhotra (✉)
Department of Electronics and Communication Engineering,
G.N.D.U. Regional Campus,
Jalandhar, India
e-mail: jyoteesh@rediffmail.com

A. K. Sharma
Department of Computer and Science Engineering,
National Institute of Technology,
Jalandhar, India
e-mail: sharmaajayk@rediffmail.com

R. S. Kaler
Department of Electronics and Communication Engineering,
Thapar University,
Patiala, India
e-mail: rskaler@yahoo.com

Keywords Wireless channel modeling · Digital modulation · Outage probability · Average bit error rate · Moment generating function · Padé approximation

1 Introduction

Wireless systems suffer from problems introduced by multipath fading and shadowing. Considerable efforts have been devoted to statistically model these effects. Depending on the radio propagation environment and the underlying communication scenario, there is a range of statistical multipath fading models available in the literature [1]. Due to the ever-increasing demand and ubiquitous access of personal communication services, wireless systems are required to operate in increasingly hostile environments. Therefore, wireless system designers must understand the radio environment in order to adequately predict the performance of mobile radio systems. A versatile wireless channel model, which can generalize the commonly used models for multipath fading and shadowing, is the two-parameter generalized gamma model [2–4, 12]. It includes multipath fading models such as Rayleigh, Nakagami-m, and Weibull as special cases and lognormal shadowing model as the limiting case. The generalized gamma model demonstrated a superior fit to the measured data over a wide range of physical channel conditions in [3]. Average bit error rate (ABER) expressions for binary phase shift keying (BPSK) and binary frequency shift keying (BFSK) were presented as infinite series in [3]. The closed form expressions specifically for BPSK and BFSK modulation in terms of MeijerG and Fox's H special functions were presented in [2]. Thus, their applicability is limited because we are not aware of any computer program for evaluating the Fox's H function. Thus, a unified and easy to compute performance analysis for the signal-to-noise ratio (SNR) statistics of a receiver operating over generalized gamma fading is required. In this paper, Padé approximation (PA) technique has been used to obtain a simple way to evaluate rational expressions for the moment generating function (MGF) of generalized-gamma random variable (RV). Using these novel MGF expressions, we study the signal outage and ABER of important digital modulation schemes for single channel receiver operating on generalized gamma fading channel. Earlier, the PA technique was used for performance analysis of diversity systems in Nakagami-m fading [5] and more recently in Weibull fading channels [6]. The generalized gamma fading model has also been used recently for switched diversity combining system in [11]. In this analysis, the amount of fading [1] demonstrates how the generalized gamma model unifies the Rayleigh, Nakagami-m, and Weibull fading channels. The effect of fading severity on the performance is investigated. Computer simulations are also generated for the result verifications.

The rest of the paper is organized as follows. In the following section, we present our system and channel model and illustrate how the PA technique can be efficiently used to obtain the MGF of the output SNR. Section 3 details the performance analysis of the system in terms of amount of fading, average BER, and outage probability. The proposed technique is then demonstrated by numerical and simulation results in Section 4 before the paper is finally concluded in Section 5.

2 System and channel model

We consider signal transmission over slow, frequency-nonselective generalized gamma fading channel. The baseband representation of the received signal is given by $y=sx+n$, where s is the transmitted baseband symbol that can take different values from modulation alphabets such as M-quadrature amplitude modulation (MQAM) and M-phase shift keying (MPSK), x is the channel shadowed-fading envelope, which is generalized gamma distributed, and n is the additive white Gaussian noise. The probability density function (PDF) of the generalized gamma RV is given in [2, 3]:

$$f_X(x) = \frac{2vx^{(2vm-1)}}{\Gamma(m)(\Omega/m)^m}\exp\left(-\frac{mx^{2v}}{\Omega}\right) \quad x \geq 0 \tag{1}$$

where v and m are fading parameters, Ω the scaling parameter and $\Gamma(.)$ is the gamma function. The fact that this distribution has one more parameter than the well-known distributions renders it more flexible. For wireless systems, Eq. 1 provides a versatile and simple way to model all forms of channel fading conditions including shadowing. By varying the two parameters v and m, different fading and shadowing conditions can be described. For instance, v=1, Eq. 1 represent Nakagami fading; m=1, Eq. 1 represent Weibull fading; m=v=1 Eq. 1, represent Rayleigh fading. The lognormal distribution used to model shadowing may also be well approximated for $m\to\infty$ and $v\to 0$. It is well known that the performance of any communication system, in terms of bit error rate (BER) and signal outage will depend on the statistics of the SNR. From [1], the instantaneous SNR per received symbol is $\gamma = \frac{x^2 E_b}{N_0}$ and the average SNR is $\overline{\gamma} = \frac{E[x^2]E_b}{N_0}$ where $E[.]$ denotes expectation, E_b is the average signal energy per bit and N_0 representing single sided power spectral density of the AWGN. From the RV transformation given in [1], the PDF of instantaneous SNR per received bit will be

$$f_\gamma(\gamma) = \left(\frac{\Gamma\left(m+\frac{1}{v}\right)}{\Gamma(m)\overline{\gamma}}\right)^{mv}\frac{v\gamma^{vm-1}}{\Gamma(m)}\exp\left\{-\left(\frac{\Gamma\left(m+\frac{1}{v}\right)\gamma}{\Gamma(m)\gamma}\right)^v\right\} \gamma \geq 0 \tag{2}$$

To find nth order moment using Eq. 2, an integral of the form $I = \int_0^\infty \gamma^{n+vm-1}\exp\left\{-\left(\Gamma\left(m+\frac{1}{v}\right)\gamma/\Gamma(m)\overline{\gamma}\right)^v\right\}d\gamma$ needs to be solved. By applying transformation y^v=t and using ([7], Eq. 3.381.4), in I the closed form expression of nth moment of γ output SNR is obtained as

$$E[\gamma^n] = \overline{\gamma}^n\frac{\Gamma\left(m+\frac{n}{v}\right)\Gamma^{n-1}(m)}{\Gamma^n\left(m+\frac{1}{v}\right)} \tag{3}$$

In order to quantify the performance in terms of ABER and signal outage, well-known MGF based unified approach [1] will be used. We will use PA technique to find simple to evaluate rational expressions for the MGF as follows.

The MGF of an RV γ>0 is

$$M_\gamma(s) = E[e^{-sx}] = \int_0^\infty e^{-s\gamma}f_\gamma(\gamma)d\gamma \tag{4}$$

Using the Taylor series expansion of e^{-sy} the MGF given by Eq. 4 can be expressed in terms of a power series as

$$M_\gamma(s) = \sum_{n=0}^\infty \frac{(-1)^n}{n!}E(\gamma^n).s^n = \sum_{n=0}^\infty c_n s^n \tag{5}$$

where $c_n = \frac{(-1)^n}{n!}\overline{\gamma}^n\frac{\Gamma(m+n/v)\Gamma^{n-1}(m)}{\Gamma^n(m+1/v)}$

The infinite series in Eq. 5 is not guaranteed to converge for all values of s. But it is possible, using PA technique, to obtain efficiently the limiting behavior of a power series in compact rational function form [8, 9]. In particular, the one-point PA of order ($D-1/D$) is defined from the series Eq. 5 in a rational function form by

$$M_\gamma(s) \simeq \frac{\sum_{i=0}^{D-1} a_i s^i}{\sum_{j=0}^{D} b_j s^j} \tag{6}$$

where a_i and b_j are the coefficients such that

$$\frac{\sum_{i=0}^{D-1} a_i s^i}{\sum_{j=0}^{D} b_j s^j} = \sum_{n=0}^{2D-1} c_n s^n + O\left(s^{2D}\right) \tag{7}$$

where $O(s^{2D})$ representing the terms of order higher than $2D-1$. The coefficients b_j can be found using (assuming $b_0=1$) following equations

$$\sum_{j=0}^{D} b_j c_{D-1-j+l} = 0 \qquad 0 \le l \le D \tag{8}$$

The above equations form a system of D linear equations for the D unknown denominator coefficients in Eq. 6. This system of equations can be uniquely solved, as long as the determinant of its Hankel matrix is nonzero [8]. The choice of the value of D is indeed a critical issue, as it represents a tradeoff between the accuracy of the PA technique and the complexity of the system of equations to be solved. It is described in [8] that there exist a value of D above which Hankel matrix become rank deficient. After solving for the values of b_j, the set a_i can now be obtained from

$$a_i = c_i + \sum_{p=1}^{\min(D,i)} b_i c_{i-p} = 0 \qquad 0 \le i \le D-1 \tag{9}$$

Having obtained the coefficients of denominator and numerator polynomials, an appropriate expression for the MGF of the output SNR is now available in rational function form. We are now ready to present three important performance measures, namely, the amount of fading (AF), the ABER for different modulation schemes, and outage probability in the generalized gamma fading channel.

3 Performance analysis

In this section, the performance of various classes of receivers operating over generalized gamma fading channel is presented, in terms of AF, ABER, and outage probability.

3.1 Amount of fading

The AF is an important statistical characterization of the fading channel, which can be easily obtained from Eq. 3, using [1] as

$$AF = \frac{E[\gamma^2]}{\gamma^2} - 1 = \frac{\Gamma(m+2/v)\Gamma(m)}{\Gamma^2(m+1/v)} - 1 \tag{10}$$

The different channel fading conditions can be described using AF, with AF=0 corresponding to an ideal Gaussian Channel and AF=∞ to severe fading. When $m\to\infty$ and $v\to\infty$, AF becomes 0; we have ideal channel condition, i.e., no fading. The plot of AF is shown in Fig. 1.When $m=v=1$, AF becomes 1; we have Rayleigh fading. When $v=1$, we have Nakagami fading channel dependent on m. In addition, the AF reduces to $1/m$ for $v=1$, same as computed in ([1], eq.2.24) for Nakagami-m fading. The values of parameter $v<1$ give more severe fading conditions than are possible with Nakagami model. Substituting $m=1$ in Eq. 10, AF exactly matches with ([1], eq.2.36), i.e., AF of Weibull fading Channel with $c=2v$.

3.2 Average bit error rate

1. M-quadrature amplitude modulation (MQAM)

In the single channel receiver, the conditional BER of Gray encoded MQAM in [10] and using alternative Gaussian-Q function form in [1], is given as

$$P_b(\gamma_b) = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\log_2(M)} \times \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} \exp\left(-\frac{(2i+1)^2}{2\sin^2\phi}\frac{3\log_2(M)}{(M-1)}\gamma_b\right) d\phi \tag{11}$$

where γ_b is the instantaneous SNR per bit. Averaging over the PDF of the received SNR the ABER becomes

$$\overline{P}_b = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\log_2(M)} \times \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} M_\gamma\left(\frac{(2i+1)^2}{2\sin^2\phi}\frac{3\log_2(M)}{(M-1)}\right) d\phi \tag{12}$$

Where $M_\gamma(.)$is the MGF of generalized gamma distributed RV

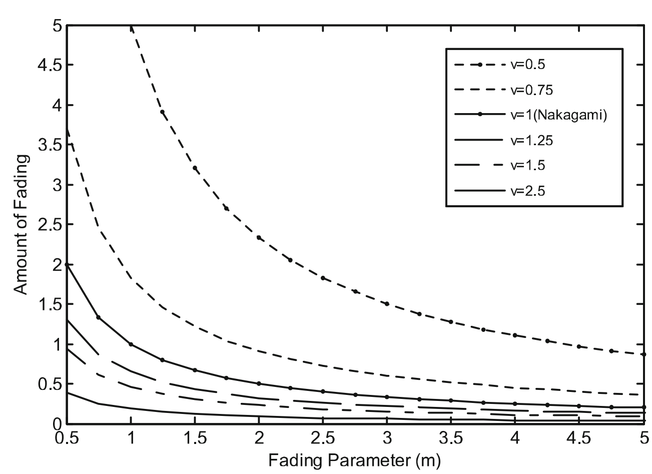

Fig. 1 Amount of fading as a function of m for several values of v

2. M-phase shift keying (MPSK)

In the single channel receiver, the conditional BER of Gray-encoded MPSK in [10] and using alternative Gaussian-Q function form in [1], is given as

$$P_b(\gamma_b) \cong \frac{2}{\pi \max(\log_2(M),2)} \times \sum_{i=1}^{\max(M/4,1)} \int_0^{\pi/2} \exp\left(-\sin^2 \frac{(2i-1)\pi}{M} \frac{\log_2(M)}{\sin^2\phi} \gamma_b\right) d\phi \tag{13}$$

Averaging over the PDF of the received SNR the ABER becomes

$$\overline{P}_b \cong \frac{2}{\pi \max(\log_2(M),2)} \times \sum_{i=1}^{\max(M/4,1)} \int_0^{\pi/2} M_\gamma\left(\sin^2 \frac{(2i-1)\pi}{M} \frac{\log_2(M)}{\sin^2\phi}\right) d\phi \tag{14}$$

3. Binary phase shift keying

As given in [1], for single channel binary phase shift keying receiver with coherent detection (CBPSK), he conditional BER is $P_b(\gamma) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{\gamma}{\sin^2(\theta)}\right) d\theta$, and with differentially coherent detection (BDPSK), the conditional BER is $P_b(\gamma)=0.5\ \exp(\gamma)$. Using MGF approach, ABER will be

$$\overline{P}_b = \frac{1}{\pi} \int_0^{\pi/2} M_\gamma\left(\frac{1}{\sin^2(\theta)}\right) d\theta \tag{15}$$

$$P_b = .5 M_\gamma(1) \tag{16}$$

Equations 15 and 16 give ABER for CBPSK and BDPSK, respectively.

3.3 Outage probability

The signal outage probability is defined as the probability that the instantaneous SNR falls below a certain threshold, i.e.

$$P_{\text{out}}(\gamma_{\text{th}}) P(\text{SNR} < \gamma_{\text{th}}) \tag{17}$$

For single channel receiver, using MGF approach ([1], Chap. 1), the outage probability can be computed as

$$P_{\text{out}}(\gamma_{\text{th}}) = \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{M_\gamma(s)}{s} e^{s\gamma_{th}} ds \tag{18}$$

where ε is a properly chosen constant in the region of convergence of complex s-plane. Interestingly, since $M_\gamma(s)$ is given in terms of a rational function, one can use the partial fraction expansion of $[M_\gamma(s)]/s$ in Eq. 18 to evaluate outage probability, i.e.

$$\begin{aligned} P_{\text{out}}(\gamma_{\text{th}}) &= \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \sum_{i=1}^{N_p} \frac{\lambda_i}{s + p_i} e^{s\gamma_{th}} ds \\ &= \frac{1}{2\pi j} \sum_{i=1}^{N_p} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{\lambda_i}{s + p_i} e^{s\gamma_{\text{th}}} ds \\ &= \sum_{i=1}^{N_p} \lambda_i e^{-p_i \gamma_{\text{th}}} \end{aligned} \tag{19}$$

where p_i are the N_p poles of rational function in s with λ_i its residues. Each term inside the summation in Eq. 19 represents a simple rational function form.

Clearly, using the rational function for the MGF provided by the PA technique, all the integrals in Eqs. 12, 14, 15, and 16 can be easily evaluated numerically, and the results are found to be very stable. In fact, some of the integrals, like the one in Eq. 18, closed form can be found as it is equivalent to the problem of finding the inverse Laplace transform of a rational function, which can be easily solved using the partial fractions expansion.

Table 1 Numerator and denominator coefficients of rational expressions of MGF

M	V	Representative channel Condition	Numerator coefficients $\{a_i\}$ (a_o=1)	Denominator coefficients $\{b_j\}$ (b_o=1)
1	0.75	Severe	{13.7,88.6,402.6,1382.9,3201.1,4391.6,3163.5,987.6,83.1}	{14.7,101.8,486,1755.1,4453.7,7174.4,6714.8,3258.7,658.4,29.9}
1	1	Rayleigh	{0}	{1}
1	1.5	Weibull	{0.04,-0.03,-0.1,-0.09,-0.05,-0.01,-0.001,-0.5e-4,-1.2e-7}	{1,0.3,-0.14,-0.22,-0.17,-0.08,-0.02,-0.4e-2,-0.3e-3,-0.4e-5}
1	2	Weibull	{0.6,0.2,0.05,0.8e-2,0.9e-3,0.7e-4,0.3e-5,6.6e-8,-2.8e-12}	{1.6,1.2,0.6,0.2,0.04,0.6e-2,0.6e-3,0.4e-4,0.2e-5,4.2e-8}
10	0.5	Lognormal	{3.8,3.4,-3.8,-8.8,-5.6,-1.2,-0.01,0.64e-3,-0.15e-4}	{4.8,7.5,0.75,-11.5,-15.4,-9.5,-3.1,-0.5,-0.05,-0.13e-2}
5	1	Nakagami-m	{0}	{1,2/5,2/25,1/125,1/3125}

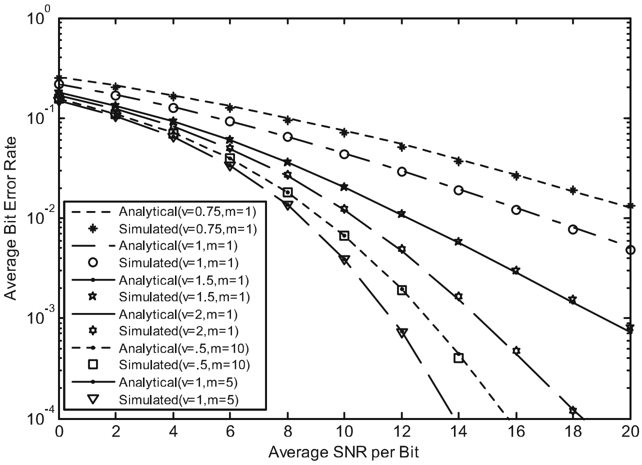

Fig. 2 Average BER of 16-QAM versus average SNR per bit of representative channel conditions using Generalized gamma model

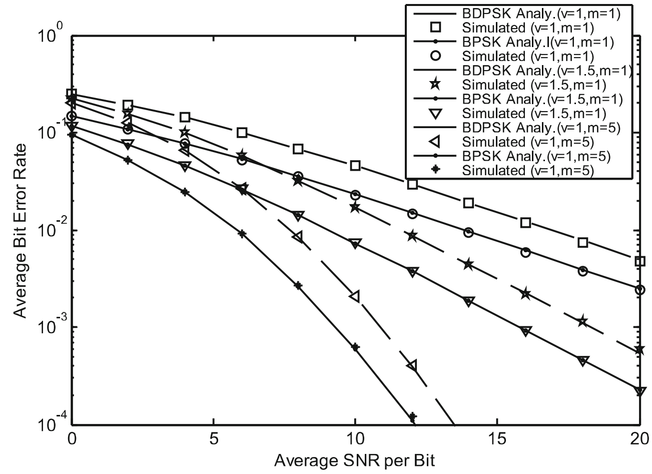

Fig. 4 Average BER of BDPSK and CBPSK vs. average SNR per bit of representative channel conditions using Generalized gamma model

4 Numerical and simulation results

We compute the rational representation using PA technique of order $D=10$. Table 1 lists the $\{a_i\}$ and $\{b_j\}$ sets for the rational function form of MGF for different values of m and v, representing various fading channel conditions. Interestingly, in special case of $m=v=1$, Hankel Matrix is rank deficient except for $D=1$, the only unknown coefficient b_1 can be easily found to be 1. The MGF found in this case is thus given by

$$M_\gamma(s) = \frac{1}{1+s\overline{\gamma}} \tag{20}$$

The above closed form expression is exactly the same expression as that of MGF of SNR given in [1] for Rayleigh faded envelope. Furthermore, in the case of ($m=5$, $v=1$), Hankel matrix is rank deficient except for $D=5$. The MGF expression found in this case is given by

$$\begin{aligned} M_\gamma(s) &= \frac{1}{1+s\overline{\gamma}+(2/5)s^2\overline{\gamma}^2+(2/25)s^3\overline{\gamma}^3+(1/125)s^4\overline{\gamma}^4+(1/3125)s^5\overline{\gamma}^5} \\ &= \frac{1}{(1+0.2s\overline{\gamma})^5} \end{aligned} \tag{21}$$

The expression 21 matches exactly with the MGF of SNR given in [1] for Nakagami-m faded envelope with $m=5$. Hence, PA technique leads to exact expressions for the special cases and compact rational expression in general, which are computationally simple for analysis. ABER of digital modulations and outage probability through generalized-gamma fading channel have been numerically evaluated using simple rational functions and compared for accuracy with simulation results. Simulation of generalized gamma distributed random variable is based on the physical description given in [4].

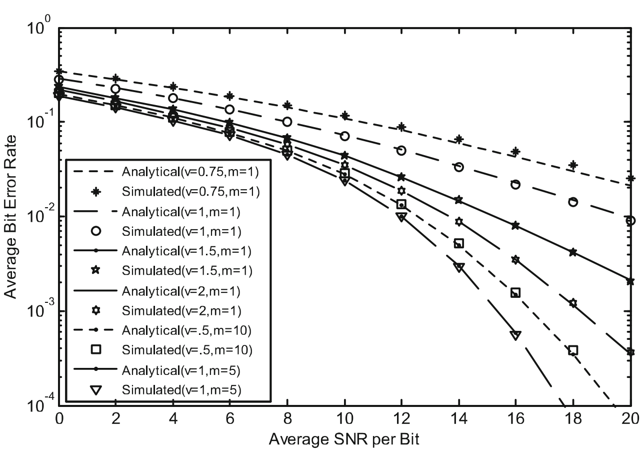

Fig. 3 Average BER of 16-PSK versus average SNR per bit of representative channel conditions using generalized gamma model

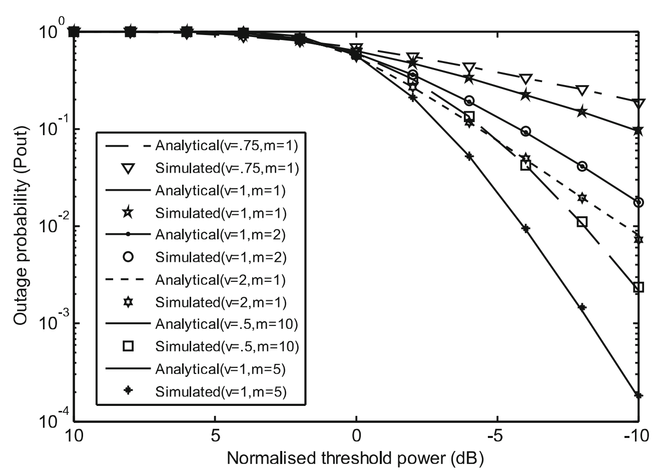

Fig. 5 Outage probability vs. normalized threshold in generalized gamma fading channel

4.1 Average BER of digital modulations

We have chosen three illustrative examples for performance evaluation of the wireless receiver in terms of average BER. The first is depicted in Fig. 2 for the case of 16-QAM and the second in Fig. 3 for the case of 16-PSK, both the two cases versus the average SNR per bit.

Computer simulation of ABER for the six representative channel fading conditions (m=1, v=0.75; m=1, v=1; m=1, v=1.5; m=1, v=2; m=10, v=0.5; m=5, v=1) is obtained and compared with results evaluated using PA technique for similar channel conditions. In Fig. 4, ABER performance of BDPSK and CBPSK is evaluated in Rayleigh, Weibull, and Nakagami fading condition using generalize gamma fading model. It is evident from the figures that the ABER improves as average SNR per bit ($\overline{\gamma}$) increases and, for a fixed value of $\overline{\gamma}$ also, ABER improves with an increase of v and/or m. As depicted, the results obtained using PA technique and computer simulations shows perfect agreement. The results obtained in [2] were based on MeijerG and Fox's H functions and were limited to binary digital modulations. The modern mathematical packages such as Mathematica and Maple fail to handle the integrals involving such special functions ([1], sec. 2.2.1.5], especially that the higher values of fading parameter m and v leads to numerical instabilities and erroneous results. The Fox's H special function cannot be evaluated using these software packages. Thus, moment-based PA technique provides an alternative simple to evaluate rational expressions, and MGF-based approach resulted in unified performance analysis of digital modulations in generalized gamma fading.

4.2 Outage probability

Figure 5 shows the outage probability versus the threshold γ_{th} normalized by scaling parameter γ. The single channel receiver signal outage probability is evaluated numerically using Eq. 18 and corroborated with Monte-Carlo simulation. It is evident from the figure that there is a perfect agreement between analytical and simulation results. Figure 5 also illustrates the effect of different representative channel fading conditions through various combinations of fading parameters v and m. It is observed that as the fading parameters v and/or m increases, the signal outage probability decreases. We observe that decreasing v for a fixed value of m increases the severity of fading. Thus, by taking different value combinations of both v and m, more variety of fading conditions can be modeled than are possible with the any of the flexible fading models such as Nakagami-m or Weibull.

From these plots, it is evident that PA technique can be used to give very accurate estimate of the MGF for arbitrary values of v and m. Note that if the accuracy is not satisfactory for some cases, it is always possible to choose a higher value of D to enhance accuracy as long as the Hankel matrix is not rank deficient.

5 Conclusions

The generalized fading model using three parameter generalized gamma distribution can describe all forms of multipath fading and shadowing seen in the wireless systems. We have analyzed the performance of wireless communication systems on a variety of fading channel conditions. In doing so, the commonly used performance measures related to wireless system design such as amount of fading, outage probability, and average bit error rate have been evaluated. Using moment-based PA technique, a simple way to evaluate rational expressions for the MGF of the receiver's output SNR are obtained. Numerical and simulation results are presented to complement the theoretical content of the paper. The results obtained from rational expressions and computer simulation shows perfect match. The existence of two fading parameters m and v makes it possible to describe different levels of fading individually or collectively. Thus, the generalized gamma model and unified analyses approach presented in this paper demonstrate a significant enhancement in the ability to evaluate the performance of wireless channels over all existing models, including the Rayleigh, Nakagami-m, Weibull, and lognormal.

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