Performance Analysis of Diversity Combining Multichannel Receivers in Generic-Gamma Fading Channels

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Abstract

In this paper, performance analysis of Optimum and Sub-optimum diversity combining receivers over generalized fading channels modeled by the three parameter Generic-Gamma model is presented. The Generic-Gamma 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 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. PA technique has been used to derive simple-to-evaluate compact rational expressions for the MGF of output SNR. Using these novel rational expressions, the performance of multichannel receivers employing diversity combining under a range of representative channel fading conditions have been evaluated. The results have been validated through simulations which shows perfect match.

Key Words: Multipath Fading, Maximal Ratio Combining, Selection Combining, Outage Probability, Average Bit Error Rate, Moment Generating Function

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 underlying communication scenario, there is range of statistical multipath fading models available in the literature [1]. Due to 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 three-parameter Generic-Gamma model [2–4]. It includes multipath fading models such as Rayleigh, Nakagami-m, & Weibull as special cases and log-normal shadowing model as the limiting case. The Generic-Gamma model demonstrated a superior fit to the measured data over a wide range of physical channel conditions in [2]. Average Bit Error Rate (ABER) expressions for binary phase shift keying (BPSK) & binary frequency shift keying (BFSK) were presented as infinite series in [2]. The closed form expressions specifically for BPSK & BFSK modulation in terms of MeijerG and Fox's-H special functions were presented in [3]. The Generic-Gamma model has also been used recently in [5] for single channel receivers analysis and generalized switched diversity combining system in [6]. However, the detailed and unified performance analysis for the SNR statistics of a diversity receivers operating over Generic-Gamma fading is not available in the open litera-

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ture and thus is the topic of our contribution. In this paper, PA technique has been used to obtain simple to evaluate rational expressions for the MGF of Generic-Gamma random variable (RV). Using these novel MGF expressions, the signal outage and ABER of important digital modulation schemes for multichannel channel receivers employing diversity combining have been evaluated. Earlier, the PA technique was used for performance analysis of diversity systems in Nakagami-m fading [7] and more recently in Weibull fading channels [8]. 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 next section, System & Channel model has been presented followed by the brief description of the PA technique that can be 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 maximal ratio combining (MRC) and sub-optimum selection combining (SC) has been used for multichannel scenario. The numerical and simulation results are discussed in section 4 before the paper is finally concluded in section 5.

2. System and Channel Model

Here the signal transmission has been considered over slow, frequency-flat Generic-Gamma fading channels. The baseband representation of the received signal is given by $y = sx + n$, where s is the transmitted baseband symbol which can take different values from modulation alphabets such as M-Quadrature Amplitude Modulation (MQAM) and M-Phase Shift Keying (MPSK), x is the channel fading envelope which is Generic-Gamma distributed, and n is the Additive White Gaussian Noise (AWGN). The Probability Density Function (PDF) of the Generic-Gamma RV is given in [2,3]

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

where ν and m are fading parameters, Ω is the scaling parameter and $\Gamma(\cdot)$ 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, (1) provides a versatile and simple way to model all forms of channel fading conditions including shadowing. By varying the two parameters ν and m, different fading conditions can be described. For instance, $\nu = 1$, (1) represents Nakagami-m fading scenario; $m = 1$, (1) represents Weibull fading scenario; $m = \nu = 1$ (1), represent Rayleigh fading. The lognormal distribution used to model shadowing may also be well approximated for $m \to \infty$ and $\nu \to 0$. 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 signal to noise ratio (SNR). From [1] the instantaneous SNR per received bit is $\gamma = \frac{x^2 E_b}{N_0}$ and the average SNR is $\bar{\gamma} = \frac{E[x^2]E_b}{N_0}$ 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

$$f_\gamma(\gamma) = \left(\frac{\Gamma\left(m+\frac{1}{\nu}\right)}{\Gamma(m)\bar{\gamma}}\right)^{m\nu} \frac{\nu\gamma^{\nu m-1}}{\Gamma(m)} exp\left\{-\left(\frac{\Gamma\left(m+\frac{1}{\nu}\right)\gamma}{\Gamma(m)\bar{\gamma}}\right)^{\nu}\right\} \quad \gamma \geq 0 \tag{2}$$

To find nth order moment using (2), an integral of the form $I = \int_0^\infty \gamma^{n+\nu m-1} \exp\{\Gamma(m+\frac{1}{\nu})\gamma / \Gamma(m)\bar{\gamma})^\nu\} d\gamma$ needs to be solved. By applying transformation $\gamma^\nu = t$ and using [[9], Eq. 3.381.4], in I the closed form expression of n^{th} moment of γ output SNR is obtained as

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

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 $\gamma > 0$ is

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

It is interesting to note that the n[th] moment of the instantaneous SNR statistics available in closed-form and is given by (3). Using the Taylor series expansion of $e^{-s\gamma}$, the MGF given by (4) can be expressed in terms of a power series as

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

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

The infinite series in (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 [10,11]. In particular, the one-point PA of order (D–1/D) is defined from the series (5) in a rational function form by

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

where a_i and b_j are the coefficients such that

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

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

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

The above equations form a system of D linear equations for the D unknown denominator coefficients in (6). This system of equations can be uniquely solved, as long as the determinant of its Hankel matrix is nonzero [10]. 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 [10] 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

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

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 Generic-Gamma fading channel.

3. Performance Analysis

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

3.1 Amount of Fading

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

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

The different channel fading conditions can be described using different AF values i.e. AF = 0 corresponds to an ideal Gaussian Channel and AF = ∞ to severe fading. For $m \to \infty$ and $v \to \infty$, AF becomes 0, which results in ideal channel condition.

The plot of AF is shown in Figure 1 corresponding to different values to fading parameters m and v. For instance, with m = v = 1, AF becomes 1 and it matches Rayleigh fading. When v = 1, we have Nakagami fading channel dependent on m. The AF reduces to $1/m$ for v = 1, which is same as computed in [[1], eq. 2.24] for

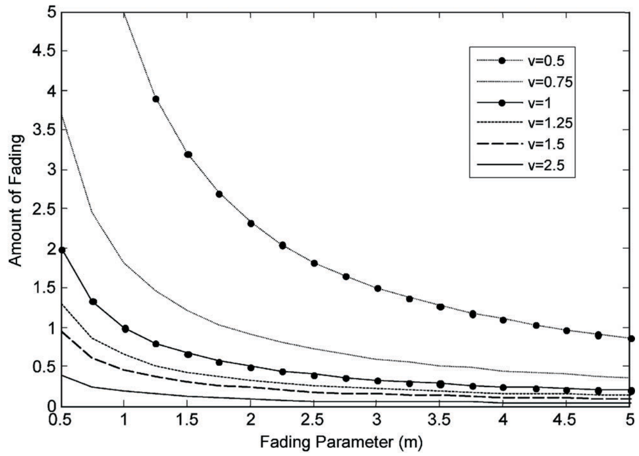

Figure 1. Amount of fading as a function of m for several values of v.

Nakagami-m fading. The values of parameter $v < 1$ give more severe fading conditions than are possible with Nakagami-m model. Substituting $m = 1$ in (10), the resulting expression exactly matches with [[1], eq. 2.36], i.e. AF of Weibull fading Channel with $c = 2v$. (c is the Weibull Fading parameter). Thus, AF illustrates the versatility of Generic-Gamma fading model in describing a range of physical channel conditions.

3.2 Average Bit Error Rate

3.2.1 M-Quadrature Amplitude Modulation (MQAM)

The conditional BER of Gray encoded MQAM in [12] and using alternative Gaussian-Q function form in [1], is given as

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

where r_b is the instantaneous SNR per bit. In MRC receiver, the total received output SNR is equal to the sum of the independent channels SNRs. For L independent and identical channels, the MGF of the output SNR is expressed as the product of the MGFs associated with each channel [1]. Thus, ABER of the MRC receiver is given by

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

where $M_\gamma(\cdot)$ is the MGF of Generic-Gamma distributed RV.

3.2.2 M-Phase Shift Keying (MPSK)

The conditional BER of Gray encoded MPSK in [12] and using alternative Gaussian-Q function form in [1], is given as

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

For the MRC receiver employing MPSK, the ABER is given by

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

3.2.3 Binary Differential Phase Shift Keying

As given in [1], binary phase shift keying receiver with differentially coherent detection (BDPSK) the conditional BER is $P_b(\gamma) = 0.5\exp(\gamma)$. The corresponding ABER of MRC receivers using MGF approach will be given as

$$\overline{P}_{MRC} = 0.5(M_\gamma(1))^L \tag{15}$$

3.3 Outage Probability

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

$$P_{out}(\gamma_{th}) = P(SNR < \gamma_{th}) \tag{16}$$

For MRC receiver with L identical & independently distributed channels, the signal outage probability is given by

$$P_{MRC\_out}(\gamma_{th}) = \frac{1}{2\pi j}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty} \frac{[M_\gamma(s)]^L}{s} e^{s\gamma_{th}} ds \tag{17}$$

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 $[M_\gamma(s)]^L / s$ in (17) to evaluate outage probability, i.e.

$$\begin{aligned} P_{out}(\gamma_{th}) &= \frac{1}{2\pi j}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty}\sum_{i=1}^{N_p}\frac{\lambda_i}{s+p_i}e^{s\gamma_{th}}ds \\ &= \frac{1}{2\pi j}\sum_{i=1}^{N_p}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty}\frac{\lambda_i}{s+p_i}e^{s\gamma_{th}}ds \\ &= \sum_{i=1}^{N_p}\lambda_i e^{-p_i\gamma_{th}} \end{aligned} \tag{18}$$

where p_i are the N_p poles of rational function in s with λ_i its residues. Each term inside the summation in (18) represents a simple rational function form.

The outage probability in case of selection combining is given by [13, sec. 7.3]

$$P_{SC\_out}(\gamma_{th}) = [F_\gamma(\gamma)]^L\Big|_{\gamma=\gamma_{th}} \tag{19}$$

where $F_\gamma(\gamma)$ is the cumulative distribution function of the Generic-Gamma RV obtained from its MGF by inverse Laplace transform as

$$F_\gamma(\gamma) = \frac{1}{2\pi j}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty}\frac{M_\gamma(s)}{s}e^{s\gamma}ds \tag{20}$$

Clearly, using the rational function for the MGF provided by the PA technique, all the integrals in (12), (14), and (15) can be easily evaluated numerically and the results are found to be very stable. In fact some of the integrals, like the one in (18) and (20) 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.

4. Numerical and Simulation Results

We compute the rational representation using PA technique of order <9/10>. Table 1 lists the $\{a_i\}$ and $\{b_j\}$ sets for the rational function form of MGF using 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

$$M_\gamma(s) = \frac{1}{1+s\overline{\gamma}} \tag{21}$$

The above closed form expression is exactly the same expression as that of MGF of SNR given in [1] for Rayleigh faded envelope. Further, 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

$$\begin{aligned} M_\gamma(s) &= \\ &\frac{1}{1+s\overline{\gamma}+(2/5)s^2\overline{\gamma}^2+(2/25)s^3\overline{\gamma}^3+(1/125)s^4\overline{\gamma}^4+(1/3125)s^5\overline{\gamma}^5} \\ &= \frac{1}{(1+0.2s\overline{\gamma})^5} \end{aligned} \tag{22}$$

The expression (22) matches exactly with the MGF of SNR given in [1] for Nakagami-m faded envelope

Table 1. Numerator and denominator coefficients of rational expressions of MGF

m	v	Representative Channel Condition	Numerator Coefficients $\{a_i\}$ ($a_0 = 1$)	Denominator Coefficients $\{b_j\}$ ($b_0 = 1$)
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}
2	1	Nakagami-m	{0}	{1, 1/4}
5	1	Nakagami-m	{0}	{1, 2/5, 2/25, 1/125, 1/3125}

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 Generic-Gamma fading channel have been numerically evaluated using simple rational functions and compared for accuracy with simulation results. Simulation of Generic-Gamma distributed random variable is based on the physical description given in [4].

4.1 ABER of Digital Modulations

Here three illustrative examples for performance evaluation of the wireless receiver in terms of ABER have been chosen. The first is depicted in Figure 2 for the case of 16-QAM, and second in Figure 3 for the case of 16-PSK, both the two cases versus the average SNR per bit. Computer simulation of ABER for the three representative channel fading conditions ($m = 1$, $v = 1$; $m = 1$, $v = 1.5$; $m = 5$, $v = 1$) is obtained and compared with results evaluated using PA technique for similar channel conditions. In Figure 4 ABER performance of BDPSK is evaluated in Rayleigh, Weibull and Nakagami fading condition using Generic-Gamma fading model. It is evident from figures that the ABER improves as average SNR per bit increases and for a fixed value of $\bar{\gamma}$ 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 [3] were based on MeijerG & Fox's H functions and were limited to binary digital modulations with single channel reception. Further, the integrals involving such special functions used there in are difficult to handle using the mathematical packages [1, sec. 2.2.1.5], such as Mathematica & Maple. Especially, the higher values of fading parameter m & v lead to numerical instabilities and erroneous results. Thus, moment based PA technique frescuted here provides an alternative simple to evaluate rational expressions and MGF based approach resulted in unified performance analysis of multichannel reception employing MRC.

4.2 Outage Probability

Figures 5 & 6 illustrate the signal outage versus the threshold normalized by scaling parameter in diversity systems employing MRC and SC, respectively. The outage probability for MRC & SC is evaluated numerically using (18) & (20), respectively. For numerical evaluation the dual channel has been considered with identical fading parameters m & v. The effect of different representative channel fading conditions through various combinations of fading parameters v and m has been illustrated in the figures. It is apparent from the figures that there is a perfect agreement between numerical and simulation results. It is observed that as the fading parameters v and/or m increases the signal outage probability decreases. This has been observed that decreasing v for a fixed value of m increases the severity of fading. As expected, the performance of Dual MRC receiver is found to be better than Dual SC receiver for any fixed value of normalized threshold. It can be seen that by taking different value

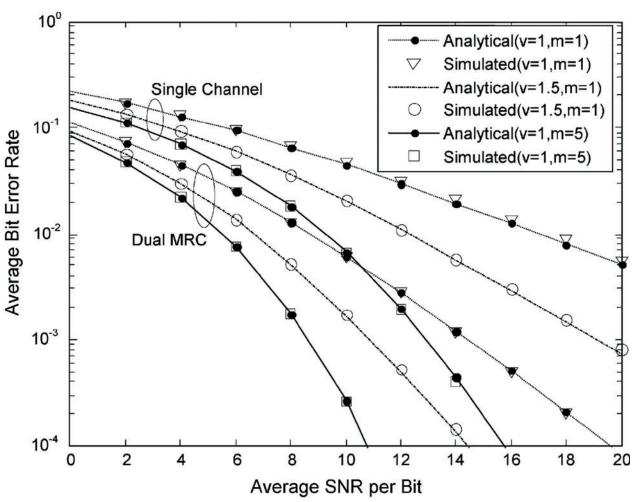

Figure 2. ABER of 16-QAM versus average SNR per bit in Generic-Gamma fading channel using MRC.

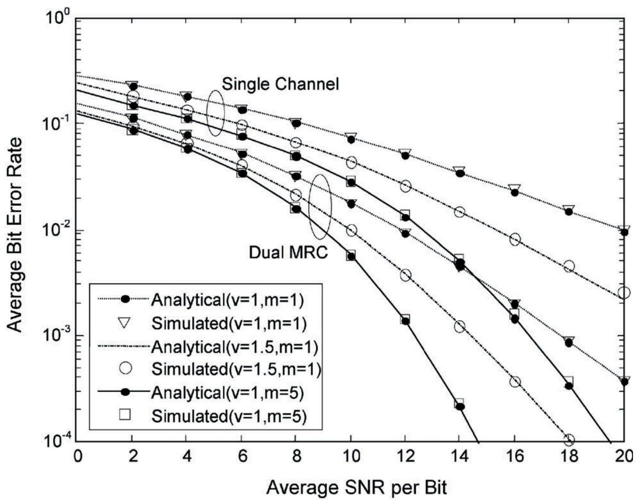

Figure 3. ABER of 16-PSK versus average SNR per bit in Generic-Gamma fading channel using MRC.

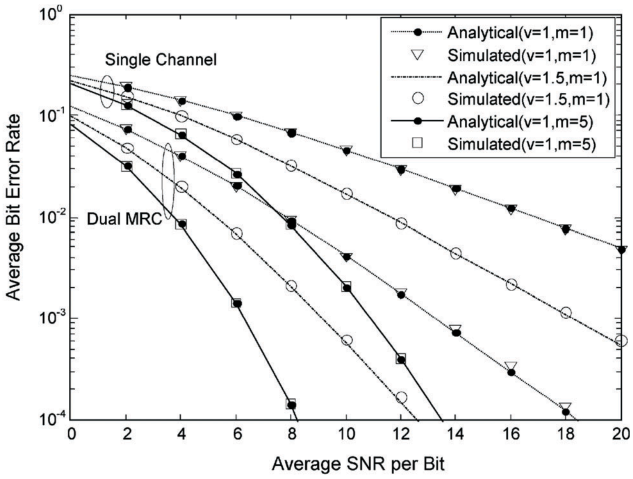

Figure 4. Average BER of BDPSK vs. average SNR per bit in Generic-Gamma fading channel using MRC.

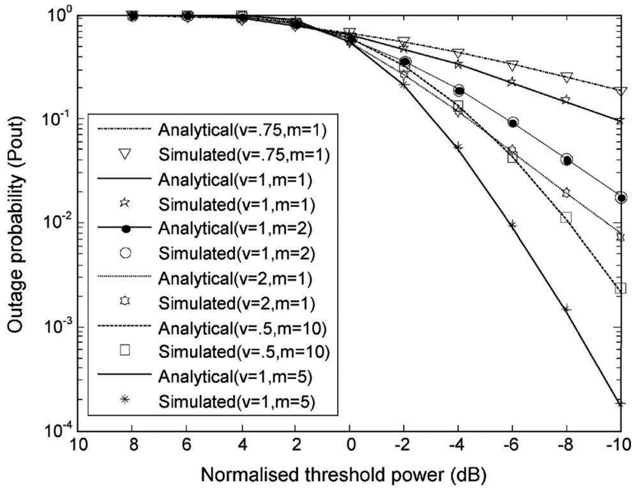

Figure 5. Outage probability vs. normalized threshold in Generic-Gamma fading channel using MRC.

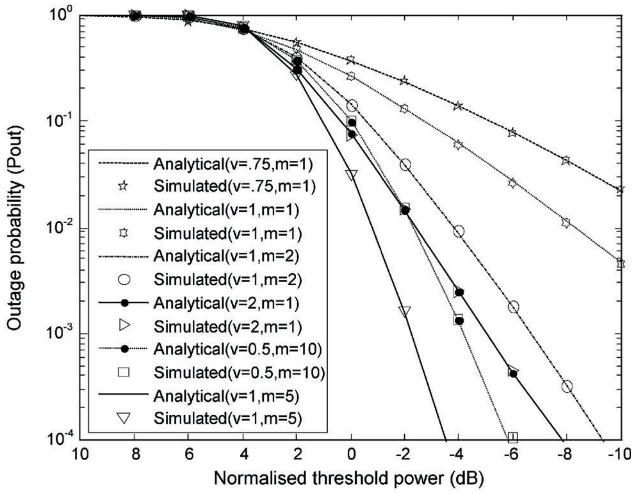

Figure 6. Outage probability vs. normalized threshold in Generic-Gamma fading channel using SC.

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. Conclusion

The generalized fading channel model based on three parameters Generic-Gamma distribution has been selected. This model embodies almost all forms of multipath fading and shadowing conditions, which has been exemplified throughout this work. The performance of multichannel wireless receiver in variety of fading channel conditions with diversity combining has been analyzed. 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 incorporated. Using moment based PA technique; simple 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 numerical evaluation of rational expressions and computer simulation shows perfect match. The existence of two fading parameters *m* and *v* make it possible to describe different levels of fading individually or collectively. Thus, the Generic-Gamma model and unified analyses approach presented here provide a significant enhancement in the ability to evaluate the multi-channel wireless system performance over all existing models, including the Rayleigh, Nakagami-m, Weibull and lognormal.

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