On the Performance Analyses in Composite Multipath-Shadowed Fading Wireless Channel

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Abstract—**The Generic-K distribution is a new flexible statistical model used to describe the composite multipath shadowed fading channels. This three parameter model is versatile enough to represent short term fading such as Rayleigh, Rician or Nakagami-m as well as shadowing. With the aid of Moment Generating Function (MGF) approach and Padé approximation (PA) technique different performance measures such as outage probability and Average bit error rate have been analyzed for a variety of modulation formats. We first use the PA technique to find simple to evaluate closed-form rational expressions for the MGF of output SNR, unlike previously obtained relatively complicated expressions in terms of MeijerG & Whittaker function. Using these simple expressions, we evaluate the performance over single and multi channel receivers under shadowed fading for arbitrary values of fading parameters. Our results are validated through computer simulations which shows perfect match.**

Keywords—Composite Shadowed fading Channel, Digital modulation, Outage Probability, Average Bit Error Rate, Moment Generating Function, Diversity reception.

I. INTRODUCTION

Wireless communication channels are impaired by detrimental effects such as Multipath Fading and Shadowing. Considerable efforts have been devoted to statistically model these effects. The constructive and destructive combination of multipath delayed, reflected, scattered and diffracted signal components leads to multipath fading. Depending on the radio propagation environment and underlying communication scenario, there is range of statistical multipath fading models [1]. Based on various indoor and outdoor empirical measurements, there is general consensus that shadowing be modeled using Log-normal distribution [2-4]. Multipath Fading models generally assume constant average signal power. But, in some situations like congested downtown areas with slow moving pedestrians and vehicles received average power also become random [2,4,5]. As a result, fading environment consist of multipath fading superimposed on shadowing, called as the Shadowed Fading Channel .This type of composite fading is also observed in Land-mobile Satellite systems subject to urban or vegetative fading [6, 7]. To model such composite Fading scenario compound statistical models based on various Fading-shadowing combinations have been suggested in the literature. The compound statistical model based on Rayleigh-Lognormal composite fading by Suzuki [2] and Hansen-Mano [4]. Other compound models based on Nakagami-Lognormal composite fading have been used in [5, 9-10]. The basis for the compound models described above is the use of Lognormal distribution for shadowing. The main drawback of these models is their complicated mathematical form which makes them inconvenient for analytical performance evaluation of wireless systems. Using the Gamma distribution as an alternative to the lognormal distribution in Rayleigh-Lognormal composite fading K-distribution was used in [11, 12]. In the past K-distribution was used for radar applications [13, 14]. But the K-distribution limits flexibility such that it is unable to fit different levels of composite fading-shadowing scenarios. A relatively new, Generic-K composite distribution has been developed, which is general enough to create most of fading-shadowing conditions observed in wireless communication channels [8, 15]. Recently, channel capacity has been evaluated in [24]. Using MGF approach [1] performance analysis of single channel wireless receiver was done in [16]. The closed form expressions used therein were in terms of Whittaker and MeijerG special functions. These closed form expressions despite the first of their kind in the open literature and having an elegant form, suffer from a major drawback. Although, the special functions used can be evaluated in itself using modern symbolic mathematical packages such as Mathematica & Maple, but these packages fail to handle integrals involving these functions [1, Sec.2.2.1.5]. Especially, the higher values of shaping parameters k & m lead to numerical instabilities and erroneous results. This renders the expressions impractical from the ease of computation point of view. Thus, it is desirable to find alternative closed-form expressions for the MGF of the Generic-K Random Variable (RV) that are simple to evaluate and at the same time suitable for higher values of *m* and *k*. In this paper, PA technique has been used to obtain simple to evaluate approximate rational expressions for the MGF of Generic-K random variable. These rational expressions are used to evaluate the ABER performance of important digital modulation schemes over the shadowed-fading channels in the case of both single and multichannel reception employing maximal ratio combining (MRC). The outage probability performance in the case of MRC and sub-optimum selection combining (SC) has also been studied. Earlier, the PA technique was used for performance analysis of diversity systems in Nakagami-m fading [17] and more recently in weibull fading channels [18]. In this analysis, we also investigate the effect of fading-shadowing severity on the performance. 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 & channel model and illustrate how the PA technique can be efficiently used to obtain the MGF of the output SNR. Section III details the performance analysis of the system in terms of ABER and outage probability. The numerical and simulation results are discussed in Section IV before the paper is finally concluded in Section V.

II. System and Channel Model

We consider signal transmission over slow, frequency-nonselective Generic-K shadowed fading channel. 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 shadowed-fading envelope which is Generic-K distributed, and *n* is the additive white Gaussian noise (AWGN). The Probability Density Function (PDF) of the Generic-K RV is given by [8]

$$f_X(x) = \frac{4m^{(k+m)/2} x^{(k+m-1)}}{\Gamma(m)\Gamma(k)\Omega^{(k+m)/2}} K_{k-m}\left\{2x\left(\sqrt{\frac{m}{\Omega}}\right)\right\} \quad x \geq 0 \quad (1)$$

where *k* and *m* are the distribution shaping parameters, $K_{k-m}\{.\}$ is the modified Bessel function of second kind and order '*k-m*'. Further, $\Gamma(.)$ is the Gamma function and Ω is the average fading power such that $\Omega \triangleq \frac{E\left[x^2\right]}{k}$, [8, eq. (7)], where $E[.]$ denotes expectation. For wireless systems, (1) provides a versatile and simple way to model all forms of fading conditions including shadowing. By varying the two shape parameters *k* and *m*, different levels of fading and shadowing can be described. When *m*=1, (1) can represent Rayleigh-lognormal or K-distribution fading [19]; higher values of *m* correspond to Shadowed-Rician fading channels [15]; for $k \to \infty$, shadowing is absent and it approximates the Nakagami-m fading. However, values of *k* in the range of 6-8 are sufficient to make the channel depend only on *m* [15].Low values of *k* and *m* correspond to severe fading and shadowing, but as both $k \to \infty$ and $m \to \infty$, (1) describes ideal channel condition (AWGN). 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 symbol is $\gamma = \frac{x^2 E_b}{N_0}$ and the average SNR is $\overline{\gamma} = \frac{E\left[x^2\right] E_b}{N_0}$ where 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 symbol will be

$$f_\gamma(\gamma) = 2\left(\frac{km}{\overline{\gamma}}\right)^{\frac{(k+m)}{2}} \frac{\gamma^{(k+m-2)/2}}{\Gamma(m)\Gamma(k)} K_{k-m}\left\{2\left(\sqrt{\frac{km\gamma}{\overline{\gamma}}}\right)\right\} \quad (2)$$

The n^{th} moment of γ is found to be [18]

$$E\left[\gamma^n\right] = \left(\frac{\overline{\gamma}}{km}\right)^n \frac{\Gamma(k+n)\Gamma(m+n)}{\Gamma(m)\Gamma(k)} \quad (3)$$

In order to quantify the performance in terms of ABER and signal outage, well known MGF approach [1] will be used. As mentioned earlier, the closed form expression of the MGF is provided in [18]. Based on discussion presented in section I, it is required to find an alternative closed-form expression for the MGF which is simpler to use in computation and valid for higher values of fading parameters. Towards that end, we will use PA technique as follows:

The MGF of an RV $\gamma > 0$ is

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

It is interesting to note that the nth 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

$$\begin{aligned} M_\gamma(s) &= \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} E(\gamma^n).s^n \\ &= \sum_{n=0}^{\infty} c_n s^n \end{aligned} \quad (5)$$

where $c_n = \frac{(-1)^n}{n!}\left(\frac{\overline{\gamma}}{km}\right)^n \frac{\Gamma(k+n)\Gamma(m+n)}{\Gamma(m)\Gamma(k)}$ 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 [20, 21]. In particular, the one-point PA of order (*D-1 /D*) is defined from the series (5) in a rational function form by

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

where a_i and b_j are the coefficients such that

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

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

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

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 [20]. 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 [20] 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

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

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 two of the most important performance measures namely, the outage probability and the ABER for different modulation schemes.

III. PERFORMANCE ANALYSIS

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

A. Average Bit Error Rate

1) M-Quadrature Amplitude Modulation(MQAM)

In the single channel receiver, the conditional BER of Gray encoded MQAM in [22] and using alternative Gaussian-Q function form in [1], is given as

$$P_b(\gamma_b) = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\, log_2(M)} \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} exp\left(-\frac{(2i+1)^2}{2\,sin^2\phi}\frac{3\,log_2(M)}{(M-1)}\gamma_b\right) d\phi \quad (10)$$

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

$$\overline{P}_b = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\, log_2(M)} \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} M_\gamma\left(\frac{(2i+1)^2}{2\,sin^2\phi}\frac{3\,log_2(M)}{(M-1)}\right) d\phi \quad (11)$$

where $M_\gamma(.)$ is the MGF of Generic-K distributed RV. In the case of 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

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

2) M-Phase Shift Keying(MPSK)

In the single channel receiver, the conditional BER of Gray encoded MPSK in [22] and using alternative Gaussian-Q function form in [1], is given as

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

Averaging over the PDF of the received SNR the ABER becomes

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

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

$$\bar{P}_{MRC} \cong \frac{2}{\pi\, max\left(log_2\left(M\right),2\right)} \times \sum_{i=1}^{max\left(M/4,1\right)} \int_0^{\pi/2} M_\gamma\left(sin^2 \frac{\left(2i-1\right)\pi}{M} \frac{log_2\left(M\right)}{sin^2 \phi}\right)^L d\phi \qquad (15)$$

3) Binary Differential Phase Shift Keying(BDPSK)

For single channel receiver employing BDPSK, the conditional BER is given by [1]

$$P_b\left(\gamma_b\right) = 0.5\, exp\left(\gamma_b\right) \qquad (16)$$

The corresponding ABER in case of single and MRC receivers using MGF approach will be given as

$$\bar{P}_b = .5 M_\gamma\left(1\right) \quad \& \quad \bar{P}_{MRC} = 0.5\left(M_\gamma\left(1\right)\right)^L \qquad (17)$$

B. Outage Probability

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

$$P_{out}(\gamma_{th}) \triangleq P\left(SNR < \gamma_{th}\right) \qquad (18)$$

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

$$P_{out}(\gamma_{th}) = \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{M_\gamma\left(s\right)}{s} e^{s\gamma_{th}} ds \qquad (19)$$

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

$$P_{MRC\_out}(\gamma_{th}) = \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{\left[M_\gamma\left(s\right)\right]^L}{s} e^{s\gamma_{th}} ds \qquad (20)$$

where $M_\gamma\left(s\right)$ is the MGF of the output SNR RV and ε is a properly chosen constant in the region of convergence of complex s-plane. Interestingly, since $M_\gamma\left(s\right)$ is given in terms of a rational function, one can use the partial fraction expansion of $\left[M_\gamma\left(s\right)\right]/s$ in (19) or $\left[M_\gamma\left(s\right)\right]^L/s$ in (20) to evaluate outage probability, i.e.

$$\begin{aligned} P_{MRC\_out}(\gamma_{th}) &= \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \sum_{i=1}^{N_p} \frac{\lambda_i}{s + p_i} e^{s\gamma_{th}} ds \\ &= \frac{1}{2\pi j} \sum_{i=1}^{N_p} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{\lambda_i}{s + p_i} e^{s\gamma_{th}} ds \\ &= \sum_{i=1}^{N_p} \lambda_i e^{-p_i \gamma_{th}} \end{aligned} \qquad (21)$$

where p_i are the N_p poles of rational function in s with λ_i its residues. Each term inside the summation in (21) represents a simple rational function form.

The outage probability in case of selection combining is given by [23, Sec.7.3]

$$P_{SC\_out}(\gamma_{th}) = \left[F_\gamma\left(\gamma\right)\right]^L \Big|_{\gamma=\gamma_{th}} \qquad (22)$$

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

$$F_\gamma(\gamma) = \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{M_\gamma\left(s\right)}{s} e^{s\gamma} ds \qquad (23)$$

Clearly, using the rational approximation for the MGF provided by the PA technique, all the integrals in (11), (12), (14), and (15) can be easily evaluated numerically and the results were found to be very stable. In fact some of the integrals, like the one in (19) 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.

IV. Numerical and Simulation Results

We compute the rational representation using PA technique of order [6/7]. Table I lists the $\{a_i\}$ and $\{b_j\}$ sets for the rational function form of MGF for different Shadowing-Fading combinations using different values of m and k. ABER of digital modulations and Outage Probability through single and multichannel Generic-K shadowed-fading channel receivers have been numerically evaluated using simple rational expressions and compared with simulation results for accuracy.

A. Average BER of M-ary Modulations

We have chosen three illustrative examples for performance evaluation of the wireless receiver in terms of average BER.

TABLE I. NUMERATOR AND DENOMINATOR COEFFICIENTS OF RATIONAL EXPRESSIONS OF MGF.

m	k	Representative Channel Condition	Numerator Coefficients {a_i} (a_0=1)	Denominator Coefficients {b_j} (b_0=1)
1	1	***Severe***	{48,835,6560,23544,33984,13068}	{49,882,7350,29400,52920,35280}
1	4	***Shadowed-Rayleigh***	{33/2,815/8,2365/8,6615/16,8085/32,12495/256}	{35/2,945/8,1575/4,11025/16,19845/32,33075/128,4725/128}
3.5	8	***Nakagami-m***	{-7.4,-25.5,23.9,-6.8,0.11,-0.19e-2}	{-6.43,-32.66,-51.4,-37.95,-13.96,-2.39,0.14}
10	5	***Shadowed-Rician***	{1.96,1.24,0.24,-6.8e-3,1.8e-4,-3.2e-6}	{2.96,3.54,2.19,0.75,0.14,1.3e-3,4.7e-4}
20	8	***Approaching ideal***	{0.95,0.15,-0.018,0.0011,-4.4e-5,9.35e-7}	{1.95,1.51,0.61,0.14,0.019,0.14e-2,0.42e-4}

The first is depicted in Fig. 1 for the case of 16-QAM, second in Fig. 2 for the case of 16-PSK, and third in Fig. 3 for the case of Binary Differential phase shift keying (BDPSK), all three versus the average SNR per bit. Computer simulation of ABER for the three representative channel conditions (m=1, k=4; m=3.5, k=8; m=20, k=8) is obtained and compared with results evaluated using PA technique for similar channel conditions. In Figures 1, 2 and 3 single and dual MRC systems are considered. It is evident from figures that the ABER improves as average SNR per bit ($\overline{\gamma}_b$) increases and for a fixed value of $\overline{\gamma}_b$ also, ABER improves with an increase of k and/or m. As expected, ABER performance of dual MRC is better than single channel system in all channel conditions for fixed value of $\overline{\gamma}_b$ .As depicted, the results obtained using PA technique and computer simulations shows perfect agreement. Thus, moments based PA technique provides an alternative simple to evaluate rational expressions and MGF based approach resulted in unified performance analysis of both single and multichannel reception employing MRC. A set of new results for higher values of fading parameters are also obtained in the shadowed-fading environment.

B. Outage Probability

We consider the two channels having identical average SNR and fading parameters m & k. Figure 4 & 5 shows the outage probability versus the threshold γ_{th} normalized by scaling parameter $\overline{\gamma}$. Fig. 4 depicts the single and dual MRC (L=2) channel receiver signal outage probability evaluated from (19) & (21) using PA technique and obtained via Monte-Carlo simulation. It is evident from the figure that there is a perfect agreement between both the curves. The effect of different representative channel fading-shadowing conditions through various combinations of fading parameters k and m has also been illustrated in figures. It is observed that as the fading parameters k and/or m increases the signal outage probability decreases. The dual SC receiver's outage probability performance evaluated from (22) using PA technique and via Monte-Carlo simulation for wide range of channel conditions is shown in Fig. 5. As expected, the performance of dual MRC receiver is found to be better than both single & dual SC receiver for any fixed value of normalized threshold.

From these plots, it is evident that rational expressions can be used to give very accurate estimate of the MGF for arbitrary values of k 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.

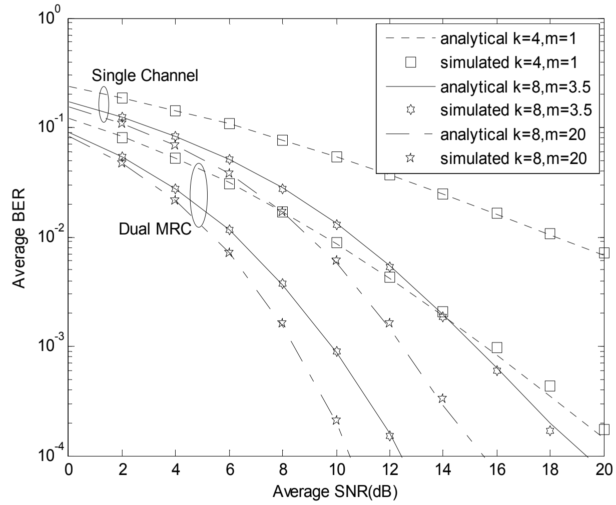

Figure 1. Average BER of 16-QAM versus average SNR per bit of representative channel conditions using PA technique and simulation.

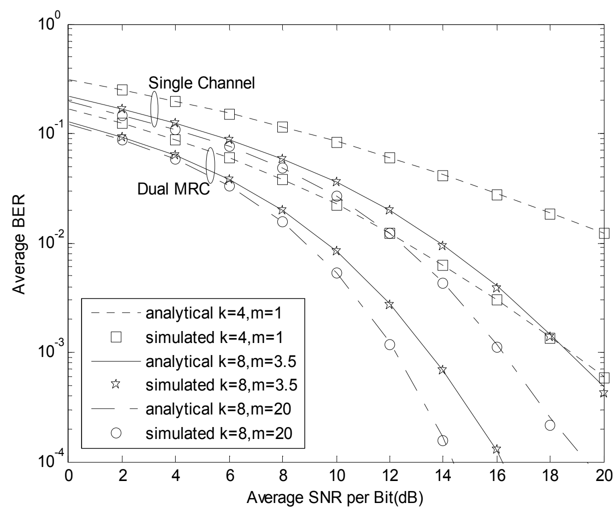

Figure 2. Average BER of 16-PSK versus average SNR per bit of representative channel conditions using PA technique and simulation.

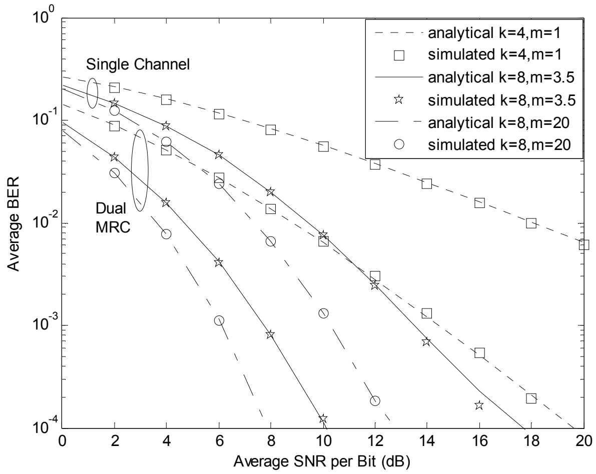

Figure 3. Average BER of BDPSK vs. average SNR per bit of representative channel conditions using PA technique and simulation.

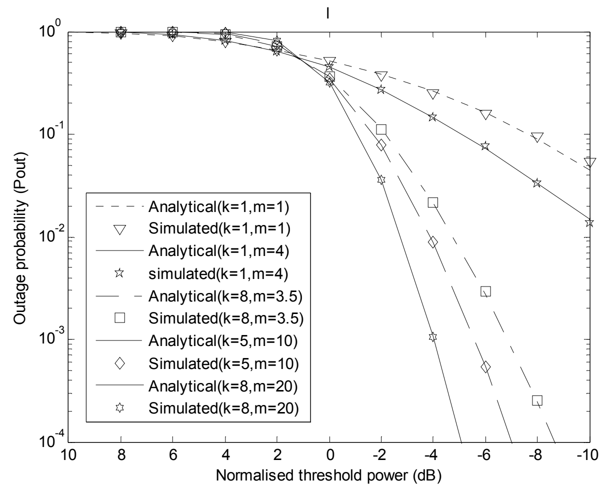

Figure 5. Outage probability vs. Normalized threshold in Shadowed-fading channel employing dual selection combinng receiver

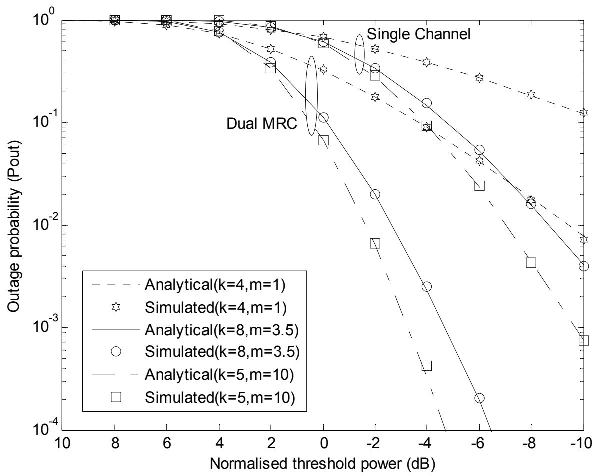

Figure 4. Outage probability vs. Normalized threshold in Shadowed-fading channel using Generic-K statistical model.

V. CONCLUSIONS.

In this paper, we have analyzed the performance of digital communication systems on shadowed fading channel using Generic-K fading model. In doing so, simple to evaluate rational expressions for the MGF of the receiver's output SNR was obtained using PA technique. Average BER and outage probability for both single and multichannel reception using MGF approach have been analyzed. Numerical and simulation results are presented to complement the theoretical content of the paper. We showed that results obtained from rational expressions using PA technique and computer simulation (using MATLAB^{TM}) match very well. We also presented a new set of results for higher fading parameter values *k* & *m*. This moment based PA technique proves to be an invaluable tool for obtaining simple, easy to evaluate, approximate closed-form and accurate expressions for the MGF, which can be used for further analysis.

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