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*Full Paper*

# Investigating the performance of single- and multichannel wireless receivers in generic-K fading channels

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**Abstract:** By using versatile generic-K statistical model, a performance analysis of wireless system has been carried out through the composite fading channel scenarios. The composite fading model used here is flexible enough to represent all forms of mixed shadowed-fading channel conditions. 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 (ABER) have been evaluated for a variety of digital modulation formats. In contrast to previously obtained relatively complicated expressions in terms of MeijerG & Whittaker special functions, the PA technique has been used here to find tractable rational expressions for the MGF of output SNR. Using these simple rational expressions, the performance evaluations have been done for both single- and multichannel receivers under different shadowed-fading channel conditions. The numerical results are also validated through computer simulations, which show a perfect match.

**Keywords:** shadowed fading channel, outage probability, average bit error rate, moment generating function, diversity reception, computational mathematics, fading channel modeling

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## INTRODUCTION

Wireless communication channels are impaired by the detrimental effects such as multipath fading and shadowing. Considerable efforts have been devoted to statistically model these effects. The constructive and destructive combinations of delayed, reflected, scattered and diffracted multipath signal components lead to multipath fading. Various multipath fading models were used in

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the past by considering different radio propagation environments and underlying communication scenarios [1a]. Based on various indoor and outdoor empirical measurements, there was a general consensus that shadowing is to be modelled using lognormal distribution [2-4]. Usually, multipath fading models assume constant average signal power, whereas it becomes random in some situations such as congested downtown areas with slow moving pedestrians and vehicles [5] and land-mobile satellite systems subject to urban or vegetative fading [6-7]. This type of mixed fading situation is referred to as composite fading or shadowed fading. Different combinations of fading-shadowing distribution have been used in the literature to model composite fading. However, much work is devoted to Rayleigh-lognormal and Nakagami-lognormal combinations [2, 4-5, 8-9]. The main drawback of these composite fading models is their complicated mathematical form due to the use of lognormal distribution for shadowing. Consequently, analytical performance evaluation becomes difficult. For analytical simplification, K-distribution, which uses gamma distribution in place of lognormal distribution, has been used as an alternative to Rayleigh-lognormal [10-12]. In the past, K-distribution was also used for radar applications [13-14]. However, it lacks flexibility and so cannot be used to fit diverse shadowed fading scenarios. A relatively new generic-K composite distribution has been proposed [15-16], which is flexible enough to create most of shadowed fading conditions observed in current wireless communication systems. By applying this model, performance analysis of single- and multichannel wireless receivers has been carried out in terms of Whittaker and MeijerG special functions [17-19]. The closed-form expressions derived therein based on these special functions, however, suffer from a major drawback despite being the first of their kind in the literature and having an elegant form. Although these special functions can be self-evaluated using modern symbolic mathematical packages (Mathematica & Maple), they fail to handle integrals involving such functions [1b]. Especially, the higher values of shaping parameters $k$ & $m$ lead to numerical instabilities and erroneous results. This renders the expressions impractical from the perspective of ease of computation. Thus, it is desirable to find alternative closed-form expressions for the moment generating function (MGF) of the generic-K random variable that are simple to evaluate and at the same time suitable for higher values of parameters $k$ & $m$.

In this paper, Padé approximation (PA) is used to obtain simple-to-evaluate rational expressions for the MGF of generic-K random variable. These expressions are used to evaluate the average bit error rate (ABER) performance of important digital modulation schemes of both single- and multichannel receivers employing maximal ratio combining (MRC). Performance evaluation is done through numerous shadowed fading scenarios represented by different values of parameters $k$ & $m$. The outage probability analysis of MRC is also performed. Earlier, the PA has been used effectively for performance analysis in generalised-Gamma, Nakagami-m and Weibull fading channels [20-22]. However, the computationally efficient and unified performance analysis with and without MRC diversity operating over generic-K fading is not available in the open literature and thus is the topic of this contribution.

**STSTEM AND CHANNEL MODEL**

Signal transmission over slow, frequency-nonselective generic-K shadowed fading channel is assumed. 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-ary quadrature amplitude modulation (MQAM) and M-ary 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) [15] of the generic-K random variable is given by

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

where $k$ and $m$ are the distribution shaping parameters, $K_{k-m}\{.\}$ is the modified Bessel function of second kind and order '*k-m*', $\Gamma(.)$ is the Gamma function and $\Omega$ is the average fading power such that $\Omega \triangleq \frac{E\left[x^2\right]}{k}$ [15], 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) characterises Rayleigh-lognormal or K-distribution fading; higher values of $m$ correspond to Shadowed-Rician fading channels [16]. 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 solely dependent on $m$ [16]. Low values of $k$ and $m$ correspond to severe fading and shadowing, but as both $k$ and $m \to \infty$, (1) describes ideal channel condition (AWGN). It is well known that the performance of any communication system in terms of ABER and signal outage depends on the statistics of the signal-to-noise ratio (SNR). The instantaneous SNR per received symbol is $\gamma = \frac{x^2 E_b}{N_0}$ and the average SNR is $\bar{\gamma} = \frac{E\left[x^2\right]E_b}{N_0}$, where $E_b$ is the average signal energy per bit [1a] and $N_0$ represents single-sided power spectral density of the AWGN. From the random variable transformation [1a], the PDF of instantaneously received SNR can be given by

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

Using (2), the $n^{th}$ moment of $\gamma$ can be found in closed form as

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

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In order to quantify the performance in terms of ABER and signal outage, the well-known MGF approach [1c] is used. Based on this approach, it is required to find alternative closed-form expressions for the MGF which are simpler to compute and valid for higher values of fading parameters. Towards that end, PA is used as described below.

The MGF of random variable $\gamma > 0$ is given by

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

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

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

where $c_n = \frac{(-1)^n}{n!}\left(\frac{\bar{\gamma}}{km}\right)^n \frac{\Gamma(k+n)\Gamma(m+n)}{\Gamma(m)\Gamma(k)}$. The infinite series in (5) is not guaranteed to converge for all values of s, but it is possible using PA to obtain efficiently the limiting behaviour of a power series in compact rational function form [23-24]. In particular, the one-point PA of order $(D-1/D)$ is defined from the series (5) in a rational form by

$$M_\gamma(s) \cong \frac{\sum_{i=0}^{D-1} a_i s^i}{\sum_{j=0}^{D} b_j s^j} \tag{5}$$

where $a_i$ and $b_j$ are the coefficients such that

$$\frac{\sum_{i=0}^{D-1} a_i s^i}{\sum_{j=0}^{D} b_j s^j} = \sum_{n=0}^{2D-1} c_n s^n + O\left(s^{2D}\right) \tag{6}$$

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

$$\sum_{j=0}^{D} b_j c_{D-1-j+l} = 0 \qquad 0 \le l \le D \tag{7}$$

The above equations form a system of $D$ linear equations having $D$ unknown denominator coefficients in (6). This system of equations can be uniquely solved as long as the determinant of its Hankel matrix is non-zero [23]. The choice of the value of $D$ is indeed a critical issue as it represents

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a trade-off between the accuracy of the PA and the complexity of the system of equations to be solved. After solving for the values of $b_j$, the set $a_i$ can now be obtained from

$$a_i = c_i + \sum_{p=1}^{min(D,i)} b_i c_{i-p} = 0 \qquad 0 \le i \le D-1 \tag{8}$$

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.

## 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.

### Averge Bit Error Rate (ABER)

*M-ary quadrature amplitude modulation (MQAM)*

In the single channel receiver, using alternative Gaussian-Q function form, the conditional bit error rate of Gray encoded MQAM [25] is given as

$$P_b(\gamma_b) = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\,log_2(M)} \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} exp\left(-\frac{(2i+1)^2}{2sin^2\phi}\frac{3log_2(M)}{(M-1)}\gamma_b\right)d\phi \tag{9}$$

where $\gamma_b$ is the instantaneous SNR per bit. Averaging over the PDF of the received SNR, the ABER becomes

$$\overline{P}_b = \frac{4\left(\sqrt{M}-1\right)}{\pi\sqrt{M}\,log_2(M)} \sum_{i=0}^{\sqrt{M}/2-1} \int_0^{\pi/2} M_\gamma\left(\frac{(2i+1)^2}{2sin^2\phi}\frac{3log_2(M)}{(M-1)}\right)d\phi \tag{10}$$

where $M_\gamma(.)$ is the MGF of generic-K distributed random variable. In the case of MRC receiver, the total received output SNR is equal to the sum of SNR of the independent channels. For $L$ independent and identical channels, the MGF of the output SNR is expressed as the product of the MGF associated with each channel [1c]. Thus, ABER of the MRC receiver is given by

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

*M-ary phase shift keying (MPSK)*

In the single channel receiver, using alternative Gaussian-Q function form, the conditional bit error rate of Gray encoded MPSK [25] is given as

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$$P_b(\gamma_b) \cong \frac{2}{\pi\, max(log_2(M),2)} \sum_{i=1}^{max(M/4,1)} \int_0^{\pi/2} exp\left(-sin^2 \frac{(2i-1)\pi}{M} \frac{log_2(M)}{sin^2\phi}\gamma_b\right) d\phi \tag{12}$$

Averaging over the PDF of the received SNR, the ABER becomes

$$\overline{P}_b \cong \frac{2}{\pi\, max(log_2(M),2)} \sum_{i=1}^{max(M/4,1)} \int_0^{\pi/2} M_\gamma\left(sin^2 \frac{(2i-1)\pi}{M} \frac{log_2(M)}{sin^2\phi}\right) d\phi \tag{13}$$

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

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

*Binary differential phase shift keying (BDPSK)*

For the single channel receiver employing BDPSK, the conditional bit error rate is given by [1c]

$$P_b(\gamma_b) = 0.5\, exp(\gamma_b) \tag{15}$$

The corresponding ABER in the case of single and MRC receivers will be given respectively as

$$\overline{P}_b = 0.5 M_\gamma(1) \text{ and } \quad \overline{P}_{MRC} = 0.5\left(M_\gamma(1)\right)^L \tag{16}$$

## Outage Probability

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

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

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

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

In the case of the MRC receiver with $L$ identical and independently distributed channels, the signal outage probability can be given by

$$P_{MRC\_out}(\gamma_{th}) = \frac{1}{2\pi j} \int_{\varepsilon - j\infty}^{\varepsilon + j\infty} \frac{\left[M_\gamma(s)\right]^L}{s} e^{s\gamma_{th}} ds \tag{19}$$

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

$$\begin{aligned} P_{MRC\_out}(\gamma_{th}) &= \frac{1}{2\pi j}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty}\sum_{i=1}^{N_p}\frac{\lambda_i}{s+p_i}e^{s\gamma_{th}}ds \\ &= \frac{1}{2\pi j}\sum_{i=1}^{N_p}\int_{\varepsilon-j\infty}^{\varepsilon+j\infty}\frac{\lambda_i}{s+p_i}e^{s\gamma_{th}}ds \\ &= \sum_{i=1}^{N_p}\lambda_i e^{-p_i\gamma_{th}} \end{aligned} \quad (20)$$

where $p_i$ are the $N_p$ poles of rational function in $s$ with $\lambda_i$ its residues. Each term inside the summation in (21) represents a simple rational function form. Clearly, using the rational approximation for the MGF provided by the PA, all the integrals in (11), (12), (14), and (15) can be easily evaluated numerically and are found to be very stable. Moreover, the closed-form expressions can also be found for the integrals given in (19) and (20) using the inverse Laplace transform of a rational function.

## NUMERICAL AND SIMULATION RESULTS

Performance evaluation results are presented here based on the analytical framework developed in the previous section. Numerical results have been obtained (using $D$ = 7) with acceptable accuracy for the target error rate of $10^{-4}$. However, it is always possible to choose a higher value of $D$ to enhance the accuracy as long as the Hankel matrix is not rank deficient. Table 1 lists the $\{a_i\}$ and $\{b_j\}$ sets for the rational function form of MGF for various shadowed fading conditions using different values of $m$ and $k$. The values of fading parameters were decisively selected to represent standard shadowed fading conditions. The ABER of digital modulations and outage probability through single- and multichannel receivers were numerically evaluated using simple rational expressions and compared for accuracy with simulation results.

**Table 1.** 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, 5040} |
| 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 | *Approached 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} |

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**ABER of M-ary Modulations**

Here, three illustrative examples for performance evaluation of the wireless receiver in terms of ABER were selected. The first is depicted in Figure 1 for the case of 16-QAM, the second in Figure 2 for the case of 16-PSK and the third in Figure 3 for the case of BDPSK, all three versus the average SNR per bit. Computer simulation results of ABER for the three representative channel conditions ($m$ = 1, $k$ = 4; $m$ = 3.5, $k$ = 8; and $m$ = 20, $k$ = 8) was obtained and compared with numerical results evaluated using PA technique for similar channel conditions. As can be seen, simulation results corroborate well the numerical results, which gives clear-cut evidence for accuracy in the derived expressions. In Figures 1-3, both single and dual MRC wireless systems are considered. It is evident from the figures that the ABER improves as average SNR per bit ($\overline{\gamma}_b$) increases and, also, for a fixed value of $\overline{\gamma}_b$, ABER improves with increase in $k$ and/or $m$. As expected, ABER performance of dual MRC is better than that of single channel system in all channel conditions for a fixed value of $\overline{\gamma}_b$.

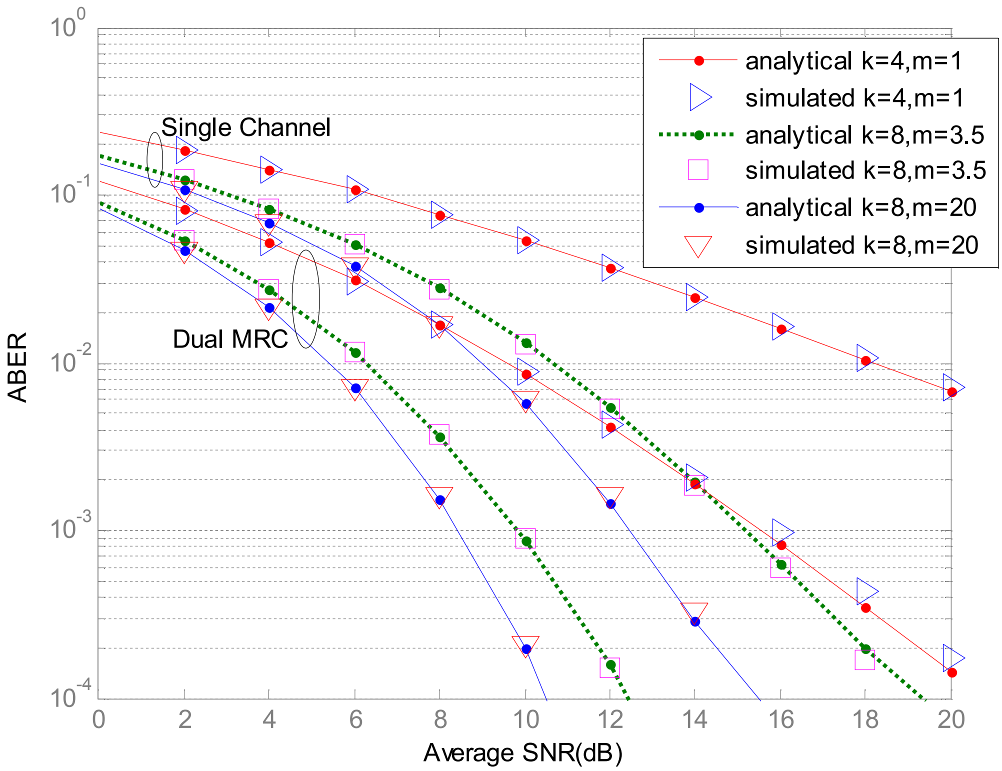


**Figure 1.** ABER of 16-QAM versus average SNR per bit of representative channel conditions

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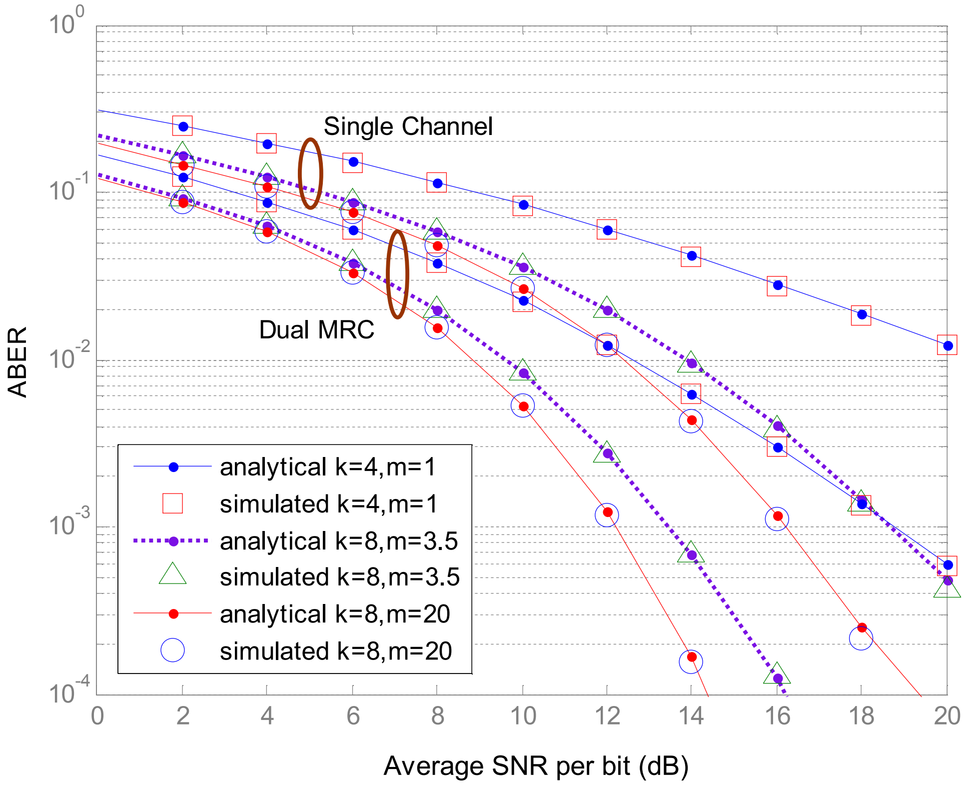


**Figure 2.** ABER of 16-PSK versus average SNR per bit of representative channel conditions

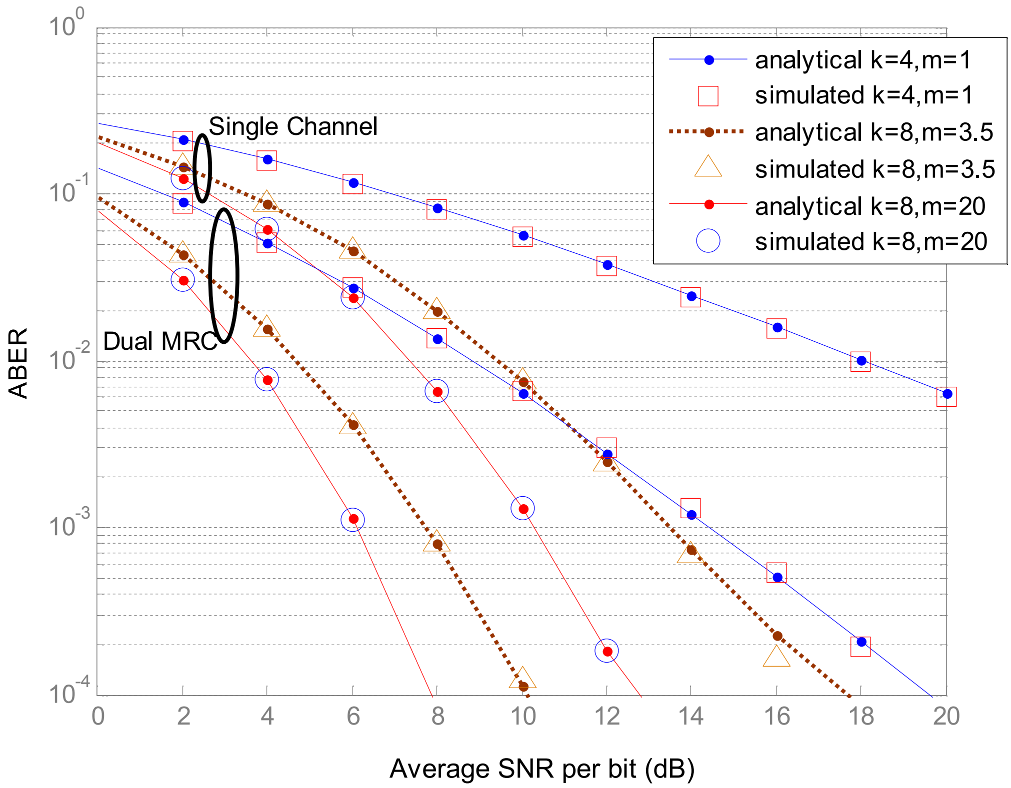


**Figure 3.** ABER of BDPSK versus average SNR per bit of representative channel conditions

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**Outage Probability**

Two channels having identical average SNR and fading parameters $m$ and $k$ outage probabilities with and without MRC were considered and evaluated. Figure 4 shows the outage probability versus the threshold $\gamma_{th}$ normalised by scaling parameter $\overline{\gamma}$. It depicts the single and dual MRC ($L$=2) channel receiver signal outage probability evaluated from (19) and (21) using PA 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 $m$ is also illustrated in Figure 4. It is observed that as the fading parameters $k$ and/or $m$ increase the signal outage probability decreases. As expected, the performance of dual MRC receiver is found to be better than that of single channel receiver for any fixed value of normalised threshold. As depicted, the results obtained using PA technique and computer simulations show perfect agreement. Thus, moment-based PA method gives alternative simple-to-evaluate rational expressions, and MGF-based approach results in unified performance analysis of both single and multichannel reception employing MRC. 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. Moreover, a new set of results have been obtained here in the shadowed fading environment for higher values of fading parameters.

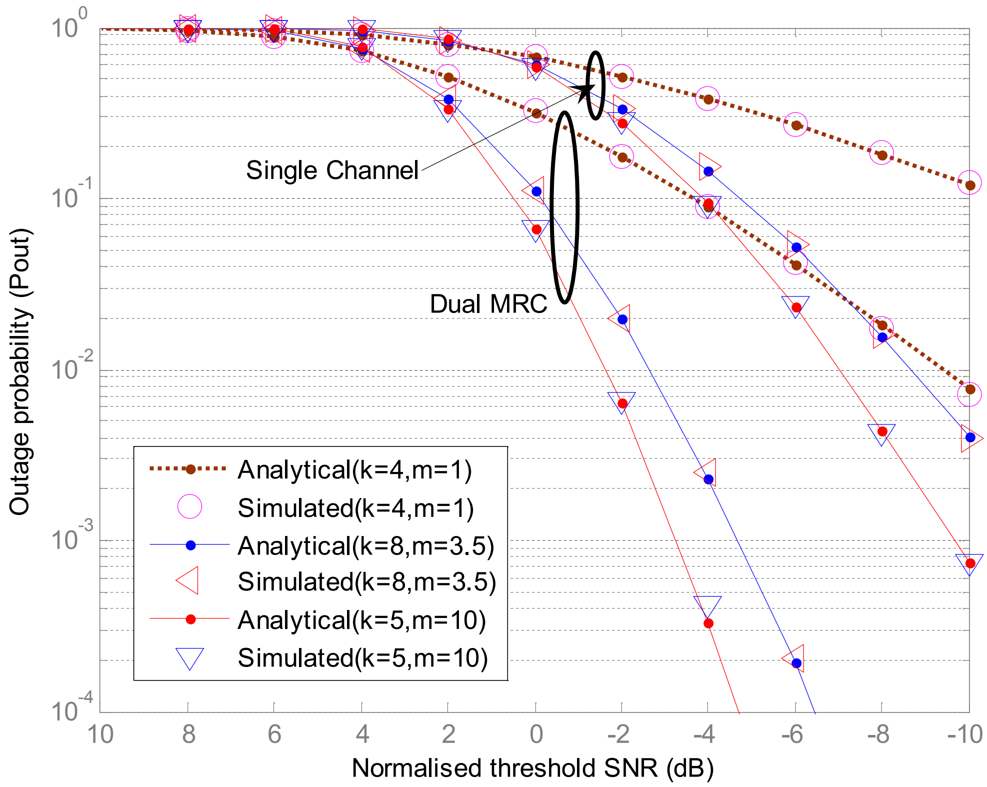


**Figure 4.** Outage probability versus normalised threshold in shadowed fading channel

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## CONCLUSIONS

The performance investigation on wireless communication systems using generic-K model was done for different shadowed-fading channel conditions. In doing so, simple-to-evaluate rational expressions for the MGF of the receiver's output SNR have been obtained using PA technique. Novel analytical expressions of ABER and outage probability for both single and multichannel receivers using MGF approach have been derived. Numerical and simulation results are presented to complement the theoretical content of the paper. It has been shown that numerical results obtained from rational expressions using PA technique and computer simulations match very well. Moreover, a new set of results for higher fading parameter values k and m have also been provided. The moment-based PA technique used here proves to be an invaluable tool for obtaining simple, easy-to-evaluate and accurate expressions for the MGF.

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