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A novel moment generating function based performance analysis over correlated Nakagami-*m* fading channels

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Abstract The bit-error rate and channel capacity have been regarded as fundamental information theoretic performance measure to predict the maximum information rate of a communication system. In contrast, with the analysis of other important performance measures of the wireless communication systems, a novel and unified general approach for computing the bit-error-rate and channel capacity over the correlated Nakagam-*m* fading channels have been proposed. In this paper, we have analyzed and numerically simulated the bit-error-rate and channel capacity of the correlated Nakagami-*m* fading channel by using the moment generating function (MGF) based approach. The derived mathematical expression for the channel capacity is in terms of the Meijer *G* function which is valid for both integer and non-integer values of the fading parameters.

Keywords Moment generating function · Average bit error rate · Correlated Nakagami-*m* fading channel · Channel capacity

1 Introduction

Wireless is the fastest growing segment of the communication market which has a wide range of services from satellites that provide low bit rates but global coverage and cellular system with continental coverage to high bit rate local area networks and personal area networks with maximum range. In the near future, we will expect seamless global roaming across different wireless networks and ubiquitous access to personalized applications rich content via a universal and user-friendly interface but still now researchers struggle with the fundamental questions about physical limitations of the communication over wireless channels. These include multi-path fading, limited spectrum resources, multiple access interference and limited battery life of the devices. The multipath fading degrades the performance of wireless communication systems. Several distributions have been discussed to model the small-scale fading such as the Rayleigh, Rician and Nakagami-*m* in detail in [1]. The Rayleigh and Rician distributions are used to characterize the channel envelop of faded signal over small geographical areas or short term fades while the log-normal distribution is used when much wider geographical areas are involved. Recently, the Nakagami-*m* fading channel model has received considerable attention due to its great flexibility and accuracy [2]. In studying the performance of wireless communication system, it is usually assumed that two signals are independent of one another. However, there are number of real-life scenario in which this assumption is not valid, for example, insufficient antenna spacing in the small-size mobile units equipped with space and polarization antenna diversity. Due to this reason, the effect of correlated fading on the performance of a diversity combining receiver has received a great deal of research interest. In the Ref. [3] and [4], the Rayleigh distribution to model the fading statistics of channel has been discussed in detail. There has been a continued interest in modeling various propagation channels with the Nakagami-*m* distribution [2], which includes Rayleigh as a special case for unit fading parameters. It is also a good approximation for the Rice distribution when fading parameter is greater than unity [5]. In the liter-

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ature, early studies on the performance of a maximal-ratio combiner in the correlated Nakagami environment concentrated either on dual-branch diversity [6] or on arbitrary diversity order with simple correlation models. The closed-form expressions for the error probability in the Nakagami fading channels with a general branch correlations is discussed in [6], taking into account the average branch signal-to-noise ratio imbalance. Though the results are general for any diversity order and arbitrary branch correlation model, the effect of antenna spacing and the operating environment on BER performance can not be evaluated from [6], due to the lack of general expression of the spatial cross-correlation coefficient.

Recently, it has been recognized that the moment generating function (MGF) is a powerful tools for simplifying the analysis of diversity communication systems, which leads to simple expression to the average bit-error-rate and symbol-error-rate for wide variety of digital signal schemes on fading channels including multi-channel reception with correlated diversity [7]. The performance analysis of switch and stay combining diversity receivers operating over the correlated Ricean fading satellite channels can be found in [7], where the performance is evaluated based on the bunch of novel analytical formulae for the outage probability, average symbol error probability, channel capacity, the amount of fading, and the average output SNR obtained in infinite series form. The similar performance analysis of the switched diversity receivers operating over the correlated Weibull fading channels in terms of outage probability, average symbol error probability, moments, and MGF can be found in [8]. Bandjur et al. [9] have studied the performance of a dual-branch switch and stay combining diversity receiver with the switching decision based on the signal to-interference ratio operating over the correlated Ricean fading channels in the presence of the correlated Nakagami-*m* distributed co-channel interference. Earlier work presented in [3, 10–13] has assumed that the frequency domain channel response samples are also the Nakagami-*m* distributed with the same fading parameters as the time domain channel. Kang et al. [14] have shown that the magnitude of frequency responses is well approximated by the Nakagami-*m* random variables with new parameters by considering only the dual diversity at receiver. Rui et al. [15] have considered the diversity at transmitter and receiver both without correlation between them but when antennas are closely spaced then signal are correlated. Du et al. [16, 17] have analyzed the performance of OFDM system over frequency selective fading channel but they have not discussed the effect of correlation on the performance of OFDM system. The performance over correlated Nakagami-*m* fading channel is analyzed by various researchers in [3, 18–20]. In the Ref. [3], Alao has been analyzed the performance over correlated Nakagami-*m* fading without the uses MGF. In the Ref. [18], Zhang uses the characteristics function method for the BER analysis. In the Ref. [19, 20], the performance analysis has been established by using the selection combining diversity.

In this paper, a novel expression for the BER for correlated Nakagami-*m* fading channel by using the MGF is derived. We also derive a closed-form-expression for the channel capacity for the proposed fading model and numerical results obtained from it are compared with the reported literature. The remainder of this paper is organized as follows. Section 2 describes the proposed channel model. Section 3 derives an expression for the MGF function. The channel capacity for the correlated Nakagami-*m* fading is derived in Sect. 4. The BER evaluation is performed in Sect. 5. Numerical results are discussed in Sect. 6. Finally, Sect. 7 concludes and recommends the future directions of the work.

2 Channel model

To evaluate the performance of a communication system with a received signal, the knowledge of the probability density function (PDF) of the resultant amplitude or envelop is of crucial importance. In this paper, we assume that the fading environment is such that the channel envelops X (combination of all the random variables), which has probability density function (PDF), given by [1]:

$$f_X(x) = \frac{2x\sqrt{\pi}}{\Gamma(m)(\sigma_1\sigma_2(1-\rho))^m}\left(\frac{x}{2\beta}\right)^{m-\frac{1}{2}} e^{-\alpha x^2} I_{m-\frac{1}{2}}(\beta x^2),$$
$$x \geq 0, \tag{1}$$

where $I_\nu(\cdot)$ denotes the νth-order modified Bessel function [21] and $\Gamma()$ is the Gamma function. x is the random variable.

$$\rho = \frac{\operatorname{cov}(r_1^2, r_2^2)}{\sqrt{\operatorname{var}(r_1^2)\operatorname{var}(r_2^2)}}, \quad 0 \leq \rho < 1,$$

is the envelop correlation coefficient between the two signals. The envelop correlation coefficient is used as measure of the degree of correlation between the fading signals. The parameters are as follows:

$$\sigma_d = \frac{\Omega_d}{m} \quad (d = 1, 2),$$
$$\alpha = \frac{(\sigma_1 + \sigma_2)}{2\sigma_1\sigma_2(1-\rho)},$$

and

$$\beta^2 = \frac{(\sigma_1 - \sigma_2)^2 + 4\sigma_1\sigma_2\rho}{2\sigma_1^2\sigma_2^2(1-\rho)^2},$$

where Ω_d, $d = 1, 2$ is the average fading signal of dth channel and m is the fading parameter. The instantaneous signal-to-noise ratio (SNR) per received symbol is:

$$\gamma = X^2 E_s/N_0,$$

where E_S is the average symbol energy and N_0 is the single sided power spectral density. The PDF of γ for the dual branch maximal ratio combing (MRC) diversity at receiver can be obtained from (1) by change of variables as given in [1]:

$$f_\gamma(\gamma) = \frac{\sqrt{\pi}}{\Gamma(m)}\left[\frac{m^2}{\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}\right]^m \times \left(\frac{\gamma}{2\beta'}\right)^{m-1/2} e^{-\alpha'\gamma} I_{m-\frac{1}{2}}(\beta'\gamma) \tag{2a}$$

where the parameters α' and β' are the normalized version of α and β and are given by:

$$\alpha' = \frac{m(\bar{\gamma}_1+\bar{\gamma}_2)}{2\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}$$

and

$$\beta' = \frac{m[(\bar{\gamma}_1+\bar{\gamma}_2)^2 - 4\bar{\gamma}_1\bar{\gamma}_2(1-\rho)]^{\frac{1}{2}}}{2\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}.$$

For the case of an identical fading channel, (2a) can be expressed as [1, (9.202)].

$$f_\gamma(\gamma) = \frac{\sqrt{\pi}}{\Gamma(m)\sqrt{1-\rho}}\left[\frac{m}{\bar{\gamma}}\right]^{m+1/2} \times \left(\frac{\gamma}{2\sqrt{\rho}}\right)^{m-\frac{1}{2}} e^{-A\gamma} I_{m-\frac{1}{2}}(B\gamma) \tag{2b}$$

where

$A = m/\bar{\gamma}(1-\rho)$, $\quad B = m\sqrt{\rho}/\bar{\gamma}(1-\rho)$ and

$\bar{\gamma} =$ Average SNR.

3 Moment generating function

Recent advances on the performance analysis of digital communication systems in the fading channel has recognized the potential importance of the moment generating function (MGF) as a powerful tool for simplifying the analysis of diversity communication systems. This has led to simple expressions to average bit-error rate and symbol error rate for variety of the digital signaling schemes on fading channels including multichannel reception with correlated diversity. The MGF is one of most important characteristics of any distribution function because it helps in the BER performance evaluation of the wireless communication systems. BER calculation is one of the most important applications of the MGF function, in some applications it can be easily evaluated if the exact knowledge of MGF is available. The MGF is defined as in [22]:

$$M_\gamma(s) = \int_0^\infty \exp(-s\gamma) f_\gamma(\gamma) d\gamma. \tag{3}$$

By substituting (2a) in (3), the MGF can be evaluated as follows:

$$\begin{aligned} M_\gamma(s) &= \int_0^\infty \exp(-s\gamma)\frac{\sqrt{\pi}}{\Gamma(m)}\left[\frac{m^2}{\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}\right]^m \\ &\quad \times \left(\frac{\gamma}{2\beta'}\right)^{m-1/2} e^{-\alpha'\gamma} I_{m-1/2}(\beta'\gamma) d\gamma \\ &= \frac{\sqrt{\pi}}{\Gamma(m)}\left[\frac{m^2}{\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}\right]^m \left(\frac{1}{2\beta'}\right)^{m-1/2} I_1, \end{aligned} \tag{4}$$

where

$$I_1 = \int_0^\infty (\gamma)^{m-1/2} e^{-(s+\alpha')\gamma} I_{m-1/2}(\beta'\gamma) d\gamma. \tag{5}$$

From [23, (3.15.1.4)] and after some mathematical manipulation, (5) can be expressed as:

$$I_1 = \frac{\sqrt{m}}{\sqrt{\pi}} \frac{(2\beta')^{m-1/2}}{[(s+\alpha')^2 - \beta'^2]^m}.$$

So the MGF for non-identical fading channel can be expressed as:

$$M_\gamma(s) = \left[\frac{m^2}{\bar{\gamma}_1\bar{\gamma}_2(1-\rho)}\right]^m \frac{1}{[(s+\alpha')^2 - \beta'^2]^m}. \tag{6}$$

For the case of identical fading and by putting the value of $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}$ in (6) reduces to

$$M_\gamma(s) = \left(1 + \frac{\bar{\gamma}(1+\sqrt{\rho})s}{m}\right)^{-m}\left(1 + \frac{\bar{\gamma}(1-\sqrt{\rho})s}{m}\right)^{-m}. \tag{7}$$

4 Average channel capacity

The channel capacity has been regarded as the fundamental information theoretic performance measure to predict the maximum information rate of the communication system. It is extensively used as the basic tool for the analysis and design of new and more efficient techniques to improve the spectral efficiency of the modern wireless communication system and to gain insight into how to counteract detrimental effects of unified approach for multipath fading propagation enabling spectral efficiency analysis. The average channel capacity in the Shannon's sense is defined by [24]

$$\bar{C} = \int_0^\infty BW \log_2(1+\gamma) f_\gamma(\gamma) d\gamma, \tag{8}$$

where BW is the transmission bandwidth of the signal. We are showing mathematical proof of the average channel capacity for identical fading channel only. Similarly, the channel capacity for non-identical fading channel also can be evaluated. From [21] and [25], (2b) can be expressed as:

$$f_\gamma(\gamma) = \frac{(\gamma m/\bar{\gamma})^{2m-1} \exp(-C\gamma)\, {}_1F_1(m, 2m, 2B\gamma)}{(\bar{\gamma}/m)(1-\rho)^m \Gamma(2m)}, \tag{9}$$

where $C = m/\bar{\gamma}(1-\sqrt{\rho})$ and ${}_1F_1[\,]$ is the confluent hypergeometric function of the first kind and after replacing ${}_1F_1[\,]$ with its infinite series representation as in [21], by using (8) and (9) with some mathematical manipulation, the average channel capacity can be expressed as:

$$\bar{C} = DBW \sum_{n=0}^{\infty} \frac{\Gamma(m+n)}{\Gamma(m)} \frac{\Gamma(2m)}{\Gamma(2m+n)} \frac{(2B)^n}{n!} I_2, \tag{10}$$

where

$$D = \left(\frac{m}{\bar{\gamma}}\right)^{2m} \times \frac{1}{(1-\rho)^m \Gamma(2m)}$$

and

$$\begin{aligned} I_2 &= \int_0^\infty \gamma^{n+2m-1} e^{-C\gamma} \log_2(1+\gamma) d\gamma \\ &= \frac{1}{\ln(2)} \int_0^\infty \gamma^{n+2m-1} e^{-C\gamma} \ln(1+\gamma) d\gamma. \end{aligned} \tag{11}$$

By substituting

$$\ln(1+\gamma) = G_{2,2}^{1,2}\left(\gamma \middle| \begin{matrix} 1 & 1 \\ 1 & 0 \end{matrix}\right)$$

in (11) as given in [26, (8.4.6.5)] and [21, (7.813.1)], (11) can be expressed as:

$$I_2 = \frac{(C)^{-2m-n}}{\ln(2)} G_{3\,2}^{1\,3}\left(\frac{\bar{\gamma}(1-\sqrt{\rho})}{m} \middle| \begin{matrix} 1-n-2m & 1 & 1 \\ 1 & 0 & \end{matrix}\right).$$

By putting the value of integral I_2 in (10) and with some mathematical manipulation, the average channel capacity can be expressed as:

$$\begin{aligned} \frac{\bar{C}}{BW} &= \frac{(F)^m}{\ln(2)} \sum_{n=0}^{\infty} \frac{\Gamma(m+n)}{\Gamma(m)} \frac{\Gamma(2m)}{\Gamma(2m+n)} \\ &\quad \times \frac{(E)^n}{n!} G_{3\,2}^{1\,3}\left(\frac{\bar{\gamma}(1-\sqrt{\rho})}{m} \middle| \begin{matrix} 1-n-2m & 1 & 1 \\ 1 & 0 & \end{matrix}\right), \end{aligned} \tag{12}$$

where $F = \frac{1-\sqrt{\rho}}{1+\sqrt{\rho}}$ and $E = \frac{2\sqrt{\rho}}{1+\sqrt{\rho}}$ and $G(\cdot)$ is Meijer's G function as given in [21, (9.301)]. The Mejjer G-function is very general function which reduces simpler special function in many common cases. It should be noted that Mejjer's G-function is widely available in many scientific software packages such as MATHEMATICA and MAPLE. A closed-form expression for the channel capacity for dual branch MRC combiner at receiver with correlated identically distributed Nakagami-m fading channel is presented in [27, (3)], but the average channel capacity provided by [27] is valid only for integer values of the fading parameters m as discussed in [28]. The mathematical expression derived for the average channel capacity in this paper which is given by (12) is valid for both integer and non-integer values of the fading parameters.

5 Average bit error rate evaluation

Depending on the particular application, the error probability can be bit-error rate or symbol error rate and is consistent with the conditional error probability. The average BER form [1, 22] for BPSK/coherent BFSK modulation scheme is:

$$\bar{P}_E = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} M_\gamma\left(\frac{g}{\sin^2\theta}\right) d\theta, \tag{13}$$

where $g = 1/2$ for BFSK and $g = 1$ for BPSK and $g = 0.715$ for coherent BFSK with minimum correlation [1]. In this paper, the mathematical proof for the average BER for an identical fading is demonstrated. Similarly, the average BER for non-identical fading can also be derived. Form (7) and (13) and with some mathematical manipulation, the average BER for identical fading can be expressed as:

$$\begin{aligned} \bar{P}_E &= \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \left(1 + \frac{\bar{\gamma}(1+\sqrt{\rho})}{m} \frac{g}{\sin^2\theta}\right)^{-m} \\ &\quad \times \left(1 + \frac{\bar{\gamma}(1-\sqrt{\rho})}{m} \frac{g}{\sin^2\theta}\right)^{-m} d\theta. \end{aligned} \tag{14}$$

By putting $t = \cos^2\theta$ and with some mathematical manipulation, (14) can be expressed as:

$$\begin{aligned} \bar{P}_E &= \frac{M_\gamma(g)}{2\pi} \int_0^1 t^{-\frac{1}{2}} (1-t)^{2m-1/2} \\ &\quad \times \left(1 - \frac{t}{1 + (\frac{\bar{\gamma}(1-\sqrt{\rho})g}{m})}\right)^{-m} \end{aligned}$$

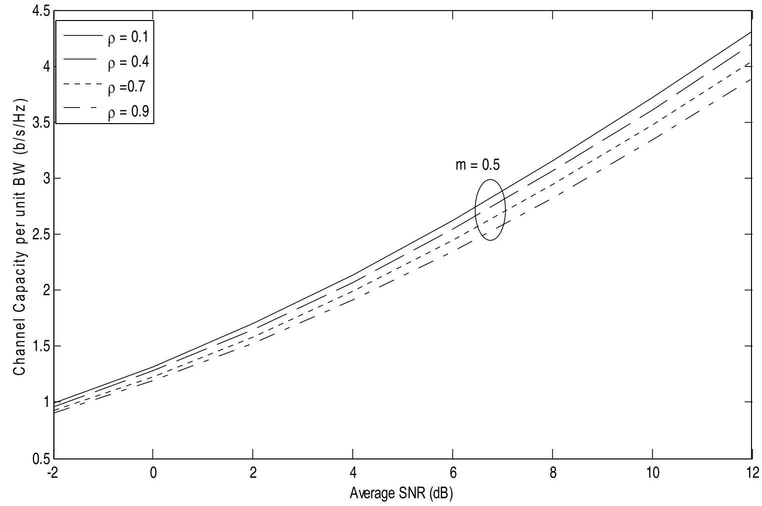


Fig. 1 The channel capacity per unit bandwidth with respect to the average signal-to-noise ratio for an identical correlated Nakagami-m fading ($m = 0.5$) channel for various values of the correlation coefficients

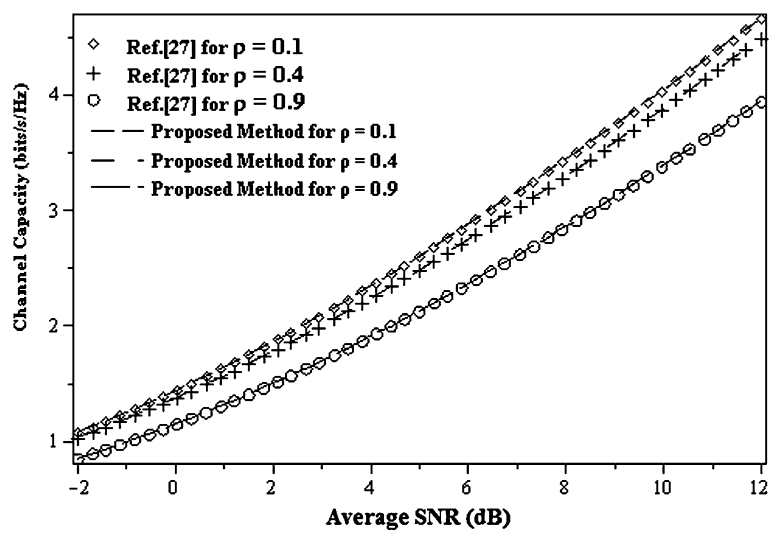


Fig. 2 Comparison of the channel capacity per unit bandwidth of an identical correlated Nakagami-m fading ($m = 1$) channel of the proposed method with [27] for various values of the correlation coefficients

$$\times \left(1 - \frac{t}{1 + (\frac{\bar{\gamma}(1+\sqrt{\rho})g}{m})}\right)^{-m} dt. \tag{15}$$

From [29, (5.8.2)], (15) can be expressed as:

$$\bar{P}_E = \frac{M_\gamma(g)}{2\pi} \frac{\Gamma(1/2)\Gamma(2m+1/2)}{\Gamma(2m+1)} \times F_1\left(\frac{1}{2}, m, m, 2m+1, \frac{1}{1+\frac{\bar{\gamma}_t(1-\sqrt{\rho})g}{m}}, \frac{1}{1+\frac{\bar{\gamma}_t(1+\sqrt{\rho})g}{m}}\right), \tag{16}$$

where F_1 is an Appell hyper geometric function as given in [29]. Equation (16) is a novel expression for the average BER analysis of the correlated Nakagami-m fading channel.

By putting $\rho = 0$ in (16), we get:

$$\bar{P}_E = \frac{(1+\frac{\bar{\gamma}g}{m})^{-2m}}{2\pi} \times \int_0^1 t^{-\frac{1}{2}}(1-t)^{2m-1/2}\left(1 - \frac{mt}{m+\bar{\gamma}g}\right)^{-2m} dt. \tag{17}$$

From [21, (3.197.3)], (17) can be expressed as

$$\bar{P}_E = B(1/2, 2m+1/2) 2F_1\left(2m, 1/2; 2m+1; \frac{m}{m+\bar{\gamma}g}\right), \tag{18}$$

where $B(\cdot)$ is the beta function as given in [2]. Form [21, (8.384)] along with [25, (15.3.3)] and [21, (8.335)], (18) can be expressed as

$$\bar{P}_E = \frac{\Gamma(4m)}{\Gamma(2m)\Gamma(2m+1)} \left(\frac{m/4}{m+\bar{\gamma}g}\right)^{2m} \left(\frac{\bar{\gamma}g}{m+\bar{\gamma}g}\right)^{1/2}$$

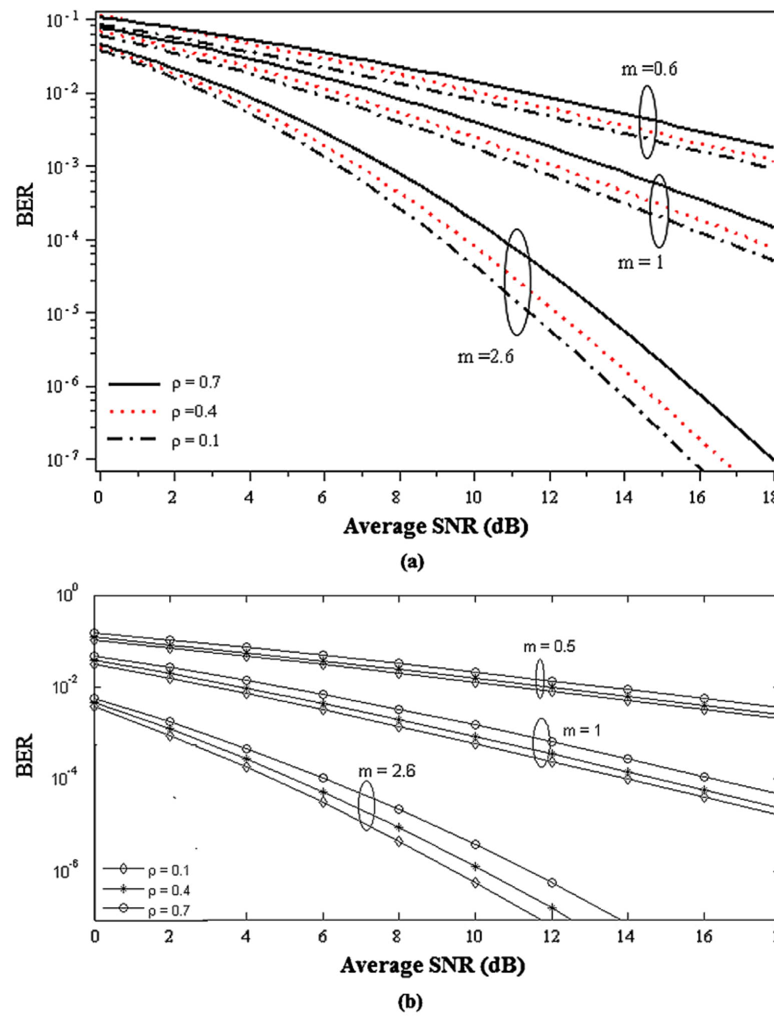


Fig. 3 The average BER analysis of the BPSK modulation scheme over the **(a)** identical and **(b)** non-identical correlated Nakagami-*m* fading channel for various values of the correlation coefficients and fading parameters

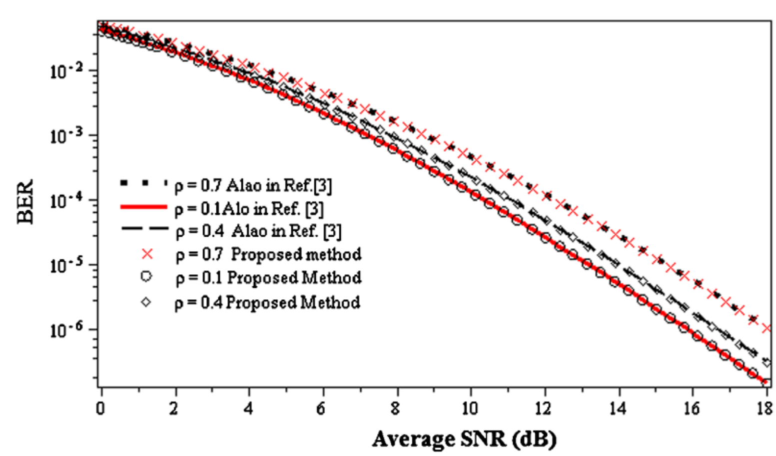
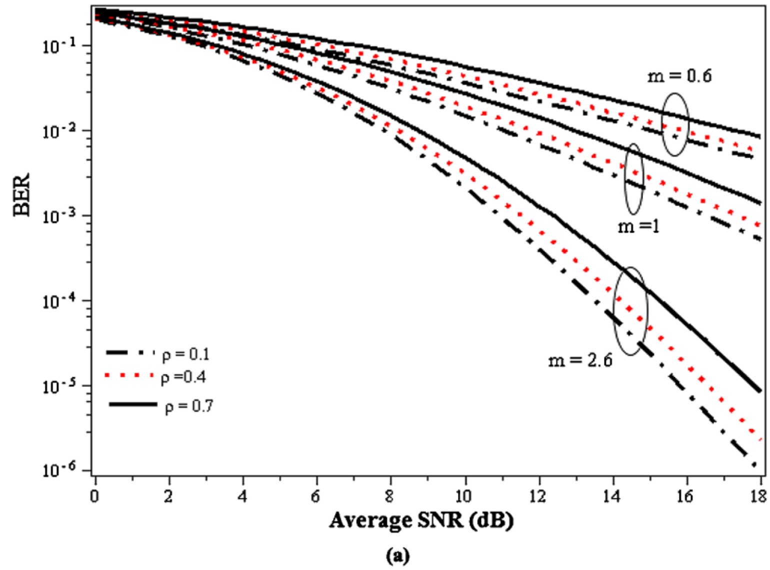


Fig. 4 Comparison of the BER characteristics of an identical correlated Nakagami-*m* fading ($m = 2$) channel of the proposed method with Ref. [3] for the various values of the correlation coefficients



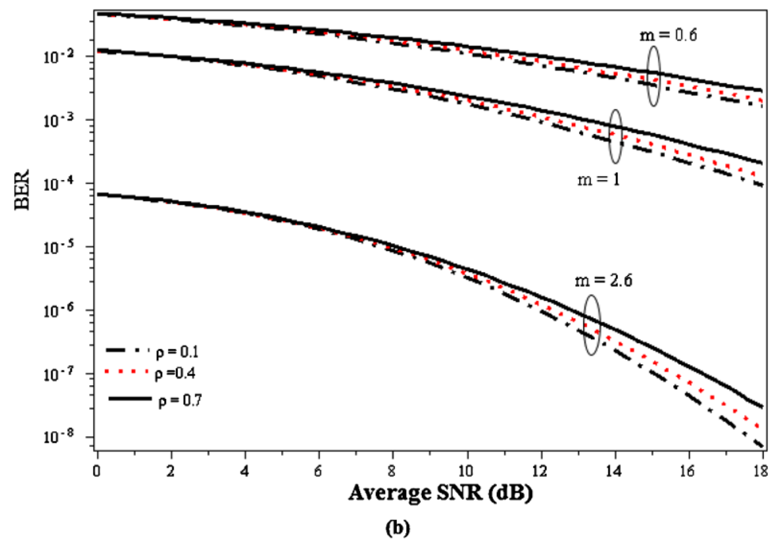


Fig. 5 The average BER analysis for non-coherent FSK (NCFSK) modulation scheme over the **(a)** identical and **(b)** non-identical correlated Nakagami-m fading channel for various values of the correlation coefficients and fading parameters

$$\times\, {}_2F_1\left(1, 2m+1/2; 2m+1; \frac{m}{m+\bar{\gamma} g}\right). \tag{19}$$

For diversity combiner ($M = 2$), (19) is similar with (30) of Ref. [3]. The average BER for differentially coherent detection of phase-shift-keying (DCPSK) or non-coherent detection of orthogonal frequency-shift-keying (NCFSK) [1] is:

$$\bar{P}_E = \frac{1}{2} M_\gamma(a_1), \tag{20}$$

where $a_1 = 1$ for DCPSK, $a_1 = 1/2$ for NCFSK as given in [1] and $M_\gamma(\cdot)$ is MGF. For the evaluation of average BER of DCPSK/NCFSK, by putting $s = a_1$ in (6) and (7) and again put $a_1 = 1$ for DCPSK and $a_1 = 1/2$ NCFSK, the average BER for the identical and non-identical correlated Nakagami-m fading can be calculated easily by using (20).

6 Results and discussion

In general, it is well known that the performance of any communication system in terms of the channel capacity and average BER is depends on the statistics of the signal-to-noise ratio (SNR). The bit-error-rate is an important property for all the digital communication systems which provides a base line for the amount of information transferred and the design depends heavily on type of channel and type of modulation. All the average BER calculations depend fundamentally on the signal-to-noise ratio at the receiver. The average BER performance of the wireless communication with received diversity over correlated Nakagami-m fading channel is analyzed and simulated for the diversity combiner at receiver ($M = 2$). When the antennas are closely spaced, the received signals are correlated. Figure 1 depicts the average channel capacity per unit bandwidth for identical correlated

Nakagami-m fading for non-integer value of the fading parameter, $m = 0.5$, by using the proposed method. The average channel capacity decreases with the increase of the numerical values of the correlation coefficient for the given SNR. For integer value of the fading parameter $m = 1$, the channel capacity of proposed method is similar with that of the Ref. [27] as shown in Fig. 2. Figure 3 shows the average BER for an arbitrary value of the fading parameter m for identical (Fig. 3(a)) and non-identical (Fig. 3(b)) fading channel. The average BER for identical as well as non-identical Nakagami fading channel improve significantly as the numerical value of the fading parameter increases for the chosen value of the average SNR but this improvement is more significant for non-identical fading channel. Figure 4 shows the comparison of the average BER with of the proposed method to the method given in [3] for various vales of the correlation coefficient. Figure 5 shows the average BER versus SNR plot for the non-coherent FSK modulation scheme over the identical correlated Nakagami-m fading channel for various values of the fading parameters m and correlation coefficient. From Fig. 5, it is seen that as the fading parameter m increases, the average BER performance improves significantly in both identical (Fig. 5(a)) and non-identical (Fig. 5(b)) correlated Nakagami fading channel and the average BER improvement is not to much significant as compare to the fading parameters with the decrease of correlation coefficient. The average BER improvement in the non-identical correlated Nakagami fading channel is more significant than that of the identical correlated Nakagami fading channel.

7 Conclusion

In this paper, we have obtained the MGF for correlated Nakagami-m fading channel, which is used to derive an expression for the average BER of BPSK/BFSK modulation schemes. The derived mathematical expressions for the average channel capacity and bit-error-rate are simple and can be reduced to other fading model in especial cases. Due to their simple forms, these results offer a useful analytical tool for the accurate performance evaluation of various systems of practical interest. We also demonstrate the effect of correlated fading channels on the channel capacity and average BER for different coherent and non-coherent modulation scheme. The proposed MGF based mathematical analysis for the computation of average BER for various coherent and non-coherent modulation schemes is easier than that reported in [3]. The proposed average BER and channel capacity results are valid for identical and non-identical fading both but Ref. [3] have not discussed average BER for non-identical fading. The average channel capacity in the manuscript has been expressed in (12) which is also valid for non-integer values of the fading parameter m. Equation (12) is an extension of (3) in [27]. In future, this proposed method can be extended for the performance analysis of equal gain diversity and selection combining diversity schemes.

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