Error analysis of *M*-QAM with equal-gain diversity over generalised fading channels

G.K. Karagiannidis, N.C. Sagias and D.A. Zogas

Abstract: *M*-ary quadrature amplitude modulation (*M*-QAM) is a spectrally efficient modulation scheme, used for video transmission applications in third and forthcoming generations of wireless networks. In the paper, the authors present a unified framework for the error performance of *M*-QAM, employing *L*-branch equal-gain combining over generalised fading channels, such as Nakagami-*m*, Rice, Hoyt or Weibull. For each channel model an exact closed-form expression is derived for the moments of the EGC output signal-to-noise ratio (SNR). Using these expressions, the symbol error performance of *M*-QAM is studied, with the aid of the moment-generating function approach and the Padé approximants theory. The proposed mathematical analysis is illustrated by selected numerical results, pointing out the effect of the input SNRs unbalancing, as well as the fading severity on the system's performance. Simulations are also performed to check the validity and the accuracy of the proposed analysis.

1 Introduction

Wireless multimedia services and products became a reality due to the advent of modern communication and information technologies and the rapid growth of the consumer market. Standards for third generation (3G) wireless communications under the umbrella of UMTS and IMT-2000 will be able to provide an information rate in the range 384 kbit/s to 2 Mbit/s, depending on the user's speed, with seamless roaming. This implies the possibility of transmitting bandwidth-greedy video and other multimedia in a wireless environment in the near future. To provide a tangible solution for foreseeable wireless video applications, wireless video transmission has been studied intensively. The *M*-ary quadrature amplitude modulation (*M*-QAM) scheme is used for transmission of video signals, as well as for digital modulated radio frequency carriers [1]. *M*-QAM is also applicable to satellite systems and to point-to-point fixed wireless networks. These signals have a higher spectral efficiency and are more robust than the conventional amplitude modulated signals with respect to noise and nonlinear distortion. However, the negative effects of fading, related to the location of the receiving antenna, are also present in the transmission of QAM modulated signals.

Diversity combining is applied in wireless communications systems to reduce the effects of fading and to improve the received signal's strength. Diversity techniques are based on the fact that errors occur in reception when the signal attenuation is large (deep fade). If the receiver is supplied with several replicas of the same signal transmitted over independent fading channels, the probability that all the received signal components be in fade simultaneously is significantly low. Various techniques are known to combine the signals from multiple diversity branches. The most popular of them are selection combining (SC), equal-gain combining (EGC) and maximal-ratio combining (MRC) [2]. EGC provides an intermediate solution as far as the performance and the implementation complexity are concerned. In EGC receivers, each signal branch is weighted with the same factor, irrespective of the signal amplitude. However, co-phasing of all signals is needed to avoid signal cancellation.

Previous related work concerning the error performance of *M*-QAM in conjunction with diversity combining schemes, include the following [2–11]. However, previously published results concerning the EGC receiver performance of *M*-QAM are scarce compared to those for other diversity methods, such as MRC, due to the difficulty of finding a useful expression for the probability density function (PDF) of the receiver's output signal-to-noise ratio (SNR). More specifically, in [7], an approach to evaluate error rates of M-QAM for EGC receivers operating in Nakagami-*m* fading environments was presented, transforming the average error integral into the frequency domain. The same method was used in [8], to evaluate error rates for several modulation schemes with EGC receivers operating in several fading environments (Rayleigh, Nakagami-*m*, Rice or Hoyt). However, the error rate expressions given for the Rice and Hoyt fading cases, include infinite range integrals and integrands composed of infinite sums of complex functions (confluent hypergeometric), due to the complex form of their characteristic functions (CHF). In [9], the error performance for several modulation schemes with EGC receivers operating over Nakagami-*m* fading channels was studied, approximating the PDF of the sum of independent Nakagami-*m* random variables (RV) by another Nakagami-*m* PDF. Recently, in [10], the authors derived an expression for the PDF of the sum of two correlated

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Nakagami-m fading envelopes and presented a converging infinite series for the average symbol error probability (ASEP) of M-QAM with dual EGC in correlated Nakagami-m fading. Finally, in [11], the authors studied the error performance of several modulation schemes, including M-QAM, for the dual EGC operating over correlated Nakagami-m fading channels, capitalising on a Parseval's theorem-based approach [8] and deriving an expression for the CHF of the sum of two correlated Nakagami-m variables.

Ascertaining the lack of a simple and unified framework to the error performance of M-QAM, when the receiver employs EGC diversity, this paper is an attempt to face this problem using a moments-based approach as an alternative method. Deriving closed-form expressions for the moments and approximating the moment-generating function (MGF) of the output SNR using Padé approximants [12], the error performance of M-QAM is accurately evaluated for the EGC receiver operating in Nakagami-m, Rice (Nakagami-n), Hoyt (Nakagami-q) or Weibull fading environments. Various numerical and computer simulations results are presented to show the simplicity and the accuracy of the proposed approach and to point out the effect of the input SNRs unbalancing, as well as the fading severity on the error performance of M-QAM.

2 Statistic of the EGC output SNR

We consider an L-branch pre-detection EGC receiver, where L antennae receive signals with statistically independent random amplitudes R_ℓ ($\ell = 1, 2, \ldots, L$) and random phases. Additive white Gaussian noise (AWGN) with identical single-sided power spectral density N_0 is added to each signal, in all branches. Moreover, the AWGN is assumed to be uncorrelated between different branches and also uncorrelated of the fading amplitudes. The EGC receiver equally weights and cophases all input signals, then sums them to produce the output signal. For equally likely transmitted symbols, the instantaneous output SNR per symbol is given by [2]

$$\gamma = \frac{E_s}{LN_0}\left(\sum_{j=1}^{L} R_j\right)^2 \tag{1}$$

where E_s is the transmitted symbols' energy. The instantaneous SNR per symbol in the ℓth input branch is

$$\gamma_\ell = R_\ell^2 \frac{E_s}{N_0} \tag{2}$$

and thus, (1) can be written as

$$\gamma = \frac{1}{L}\left(\sum_{j=1}^{L} \sqrt{\gamma_j}\right)^2 \tag{3}$$

Using (3), the kth-order moment of the EGC output SNR per symbol is by definition [13]

$$\mathcal{E}\langle \gamma^k \rangle = \frac{1}{L^k}\mathcal{E}\left\langle \left(\sum_{j=1}^{L}\sqrt{\gamma_j}\right)^{2k}\right\rangle \tag{4}$$

where $\mathcal{E}\langle \cdot \rangle$ denotes statistical averaging. Expanding the term $(\sqrt{\gamma_1} + \ldots + \sqrt{\gamma_L})^{2k}$, utilising the multinomial identity ([14], equation (24.1.2)), results in

$$\mathcal{E}\langle \gamma^k \rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1, h_2, \ldots, h_L = 0 \\ h_1 + h_2 + \ldots + h_L = 2k}}^{2k} \mathcal{E}\left\langle \prod_{j=1}^{L} \frac{\gamma_j^{h_j/2}}{h_j!}\right\rangle \tag{5}$$

For independent, but not necessarily identically distributed (i.d.), input branches the term $\mathcal{E}\left\langle \prod_{j=1}^{L} \gamma_j^{h_j/2}\right\rangle$ can be expressed as

$$\mathcal{E}\left\langle \prod_{j=1}^{L} \gamma_j^{h_j/2}\right\rangle = \prod_{j=1}^{L} \mathcal{E}\left\langle \gamma_j^{h_j/2}\right\rangle \tag{6}$$

and thus, (5) can be written as

$$\mathcal{E}\langle \gamma^k \rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1, h_2, \ldots, h_L = 0 \\ h_1 + h_2 + \ldots + h_L = 2k}}^{2k} \prod_{j=1}^{L} \frac{\mathcal{E}\left\langle \gamma_j^{h_j/2}\right\rangle}{h_j!} \tag{7}$$

Equation (7) is a simple expression for the kth-order moment of the EGC output SNR per symbol, which depends only on the SNR moments of the statistical input paths. Next, the EGC moments are derived for Nakagami-m, Rice, Hoyt and Weibull statistical models.

2.1 Nakagami-m fading

The Nakagami-m fading channel model [15] provides good fits to collected data in indoor and outdoor mobile radio environments and it is used in many wireless communications applications [16, 17]. When the receiver operates in a Nakagami-m environment, the instantaneous SNR per symbol in the ℓth input path, γ_ℓ, is a gamma distributed RV. In this case, the kth moment of γ_ℓ is given by ([2], equation (2.23)),

$$\mathcal{E}\langle \gamma_\ell^k \rangle = \frac{\Gamma(m_\ell + k)}{\Gamma(m_\ell) + m_\ell^k}\bar{\gamma}_\ell^k \tag{8}$$

where $\Gamma(\cdot)$ is the Gamma function ([14], equation (6.1.1)), $\bar{\gamma}_\ell$ represents the average input SNR and m_ℓ is the fading severity parameter, which ranges from 0.5 to ∞. Substituting (8) in (7), the moments of the receiver's output SNR are obtained in closed form as

$$\mathcal{E}\langle \gamma^k \rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1, h_2, \ldots, h_L = 0 \\ h_1 + h_2 + \ldots + h_L = 2k}}^{2k} \prod_{j=1}^{L} \bar{\gamma}_j^{h_j/2} \frac{\Gamma(m_j + k)}{h_j!\Gamma(m_j) m_j^{h_j/2}} \tag{9}$$

2.2 Rice fading

The Rice (Nakagami-n) model [18, 19] is often used to model propagation paths between the transmitter and the receiver that consist of one strong direct or line-of-sight (LOS) component and multipath components as in Rayleigh fading. When the receiver operates over Rice fading channels, the SNR of each diversity path is distributed according to a noncentral chi-square distribution. Thus, the kth moment of the SNR per symbol of the ℓth input channel is ([2], equation (2.18))

$$\mathcal{E}\langle \gamma_\ell^k \rangle = \frac{\Gamma(1 + k)}{(K_\ell + 1)^k}\,{}_1F_1(-k; 1; K_\ell)\bar{\gamma}_\ell^k \tag{10}$$

where ${}_1F_1(\cdot;\cdot;\cdot)$ is the confluent hypergeometric function of the first kind [14, Chap. 13] and K_ℓ is the Rician factor defined as the ratio of the power in specular components to the power in random components. For $K_\ell \to -\infty$ (dB) the Rayleigh fading is described, while $K_\ell \to \infty$ (dB) represents the no-fading situation. Values of the Rice factor in land mobile terrestrial (indoor and outdoor) and satellite applications usually range from 0 to 12 dB [20]. Replacing (10) in (7), the kth moment of the EGC output SNR per symbol in the Rician fading environment can be extracted in closed form as

$$\mathcal{E}\langle\gamma^k\rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1,h_2,\ldots,h_L=0\\ h_1+h_2+\ldots+h_L=2k}}^{2k} \prod_{j=1}^{L} \bar{\gamma}_j^{h_j/2} \frac{\Gamma(1+h_j/2)\,{}_1F_1(-h_j/2,\,1,\,-K_j)}{h_j!(K_j+1)^{h_j/2}} \tag{11}$$

2.3 Hoyt fading

The Hoyt (Nakagami-q) distribution [15] is normally observed on satellite links subject to strong ionospheric scintillations. When the fading amplitudes are Hoyt distributed, the kth moment of the output SNR per symbol of the ℓth input path is given by ([2], equation (2.13))

$$\mathcal{E}\langle\gamma_\ell^k\rangle = \Gamma(1+k)\,{}_2F_1\left[-\frac{k-1}{2},\,-\frac{k}{2},\,1;\,\left(\frac{1-q_\ell^2}{1+q_\ell^2}\right)^2\right]\bar{\gamma}_\ell^k \tag{12}$$

where ${}_2F_1\,(\cdot,\cdot;\cdot;\cdot)$ is the Gauss hypergeometric function ([14], equation (15.1.1)) and q_ℓ is the Hoyt fading parameter, which ranges from 0 (one-sided Gaussian fading) to 1 (Rayleigh fading). Using (7) and (12), the moments of the EGC output SNR per symbol can be expressed as

$$\mathcal{E}\langle\gamma^k\rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1,h_2,\ldots,h_L=0\\ h_1+h_2+\ldots+h_L=2k}}^{2k} \prod_{j=1}^{L} \bar{\gamma}_j^{h_j/2} \frac{\Gamma(1+h_j/2)}{h_j!}\,{}_2F_1\left[-\frac{h_j-2}{4},\,-\frac{h_j}{4},\,1;\,\left(\frac{1-q_j^2}{1+q_j^2}\right)^2\right] \tag{13}$$

2.4 Weibull fading

The Weibull distribution is a flexible model which exhibits an excellent fit to experimental fading channel measurements, for indoor [21, 22] and outdoor environments [23, 24]. The kth moment of the output SNR per symbol of the ℓth input path is given by [25]

$$\mathcal{E}\langle\gamma_\ell^k\rangle = (a_\ell\bar{\gamma}_\ell)^k\,\Gamma\left(1+\frac{2k}{\beta_\ell}\right) \tag{14}$$

where $a_\ell = 1/\Gamma(1+2/\beta_\ell)$ and β_ℓ is the Weibull fading severity parameter ($\beta_\ell \geq 1$). Using (7) and (14) the moments of the EGC output SNR per symbol can be expressed as

$$\mathcal{E}\langle\gamma^k\rangle = \frac{(2k)!}{L^k} \sum_{\substack{h_1,h_2,\ldots,h_L=0\\ h_1+h_2+\ldots+h_L=2k}}^{2k} \prod_{j=1}^{L} (a_j\bar{\gamma}_j)^{h_j/2} \frac{\Gamma(1+h_j/\beta_j)}{h_j!} \tag{15}$$

3 *M*-QAM error analysis

The error performance of M-QAM, in conjunction with EGC diversity, can be obtained by averaging the M-QAM conditional error probability P_{se}, over the PDF of the EGC output SNR [3]. Unfortunately, to the best of the authors' knowledge, a closed-form expression for this PDF is not available in the open technical literature, due to the difficulty of finding a useful form for the PDF of the sum of fading RVs, and thus the ASEP of M-QAM $\bar{P}_{se}$ cannot be directly evaluated. An alternative method to calculate the M-QAM's average error rates with EGC receivers is the MGF-based approach to the performance analysis of digital modulations over fading channels ([2], Chap. 1). Useful expressions for the MGF can be obtained using the analysis for the moments presented in Section 2 and the Padé approximants theory. The latter has been proposed by Amindavar and Ritchey to approximate unknown PDFs and cumulative distribution functions [26]. This technique has also been used in [27] by the same authors to analyse the detection performance of single and multiple pulse radar systems operating in K-distributed clutter and thermal noise.

3.1 Padé approximants to MGF of EGC output SNR

The MGF of the EGC output SNR is by definition [13]

$$\mathcal{M}_\gamma(s) = \mathcal{E}\langle\exp(s\gamma)\rangle \tag{16}$$

and can be represented as a formal power series (e.g. Taylor) as

$$\mathcal{M}_\gamma(s) = \sum_{k=0}^{\infty} \frac{s^k}{k!} g_k \tag{17}$$

where $g_k = \mathcal{E}\,\langle\gamma^k\rangle$. Although the moments g_k of all orders are finite and can be evaluated in closed forms, using the analysis of Section 2, in practice only a finite number N can be used, truncating the series as

$$\mathcal{M}_\gamma(s) = \sum_{k=0}^{N} \frac{s^k}{k!} g_k + \mathrm{O}(s^{N-1}) \tag{18}$$

where $\mathrm{O}\,(s^{N+1})$ is the remainder after the truncation, with terms of order greater than N. In many cases, we cannot conclude that the power series in (18) has a positive radius of convergence and where or whether it is convergent. Hence, we have to obtain the best approximation to the unknown underlying function $\mathcal{M}_\gamma(s)$, using only a finite number of moments. This can be efficiently achieved using the Padé approximation method, which has already been used in several scientific fields to approximate series, such as that in (18), where practically only a few coefficients are known and the series converges too slowly or diverges [12]. A Padé approximant is that rational function approximation to $\mathcal{M}_\gamma(s)$ of a specified order B for the denominator and A for the nominator, whose power series expansion agrees with the $N = A + B$ order power expansion of $\mathcal{M}_\gamma(s)$, where A and B are positive integers. If the rational function is

$$R_{[A/B]}(s) = \frac{\sum_{i=0}^{A} c_i s^i}{1 + \sum_{i=1}^{B} b_i s^i} \tag{19}$$

then $R_{[A/B]}(s)$ is said to be a Padé approximant to the series in (18), if

$$R_{[A/B]}(0) = \mathcal{M}_\gamma(0) \tag{20}$$

and

$$\frac{\partial^i}{\partial s^i} R_{[A/B]}(s)|_{s=0} = \frac{\partial^i}{\partial s^i} \mathcal{M}_\gamma(s)|_{s=0}, \quad i = 1.2, \ldots, A+B \tag{21}$$

The $A+1$ coefficients $\{c_i\}$ and the B coefficients $\{b_i\}$ are real numbers which can be obtained solving the set of $A+B+1$ equations using (20) and (21). Hence, the first $A+B$ moments are needed to be evaluated to construct the approximant $R_{[A/B]}(s)$. Padé approximants are available in most of the well known mathematical software packages, as

Table 1: Degree of Padé approximants [$A/(A+1)$] for a convergence at 5th significant digit of ASEP with equal branch SNRs, Nakagami-2 fading and $L=3$

SNR/symbol, dB	$M=4$	$M=16$	$M=64$	$M=128$
−5	[3/4]	[3/4]	[3/4]	[3/4]
0	[3/4]	[3/4]	[3/4]	[3/4]
5	[4/5]	[3/4]	[3/4]	[3/4]
10	[8/9]	[5/6]	[4/5]	[3/4]
15	[11/12]	[7/8]	[6/7]	[4/5]
20	–	[10/11]	[8/9]	[6/7]

MATHEMATICA, MATLAB and MAPLE. Next, $\mathcal{M}_\gamma(s)$ will be approximated using sub-diagonals ($B=A+1$) Padé approximants, since only in this case the convergence rate and the uniqueness can be assured [12, 26]. Moreover, the degrees of the numerator and denominator will be varied to achieve the desired accuracy for the evaluation of $\mathcal{M}_\gamma(s)$.

3.2 MGF-based approach to ASEP

According to the MGF-based approach the ASEP of M-QAM modulation scheme is given by

$$\bar{P}_{se} = \frac{4}{\pi}\left(1-\frac{1}{\sqrt{M}}\right)\left[\int_0^{\frac{\pi}{2}} \mathcal{M}_\gamma\left(-\frac{g}{\sin^2\varphi}\right)d\varphi - \left(1-\frac{1}{\sqrt{M}}\right)\int_0^{\frac{\pi}{4}} \mathcal{M}_\gamma\left(-\frac{g}{\sin^2\varphi}\right)d\varphi\right] \quad (22)$$

Using the above equation and the Padé approximants to the MGF, the error performance of M-QAM in conjunction with EGC diversity can be easily evaluated via numerical integration, since (22) consists of single integrals with finite limits and integrands composed of elementary functions (exponential and trigonometric), which behave quite well in the range of the integrals' limits.

As an indicative example, in Table 1, the degree of Padé approximants is presented that is needed to be evaluated for the convergence of the ASEP at the 5th significant digit for M-QAM signalling, several values of M and input branch SNRs, $L=3$ and identical Nakagami-m fading with $m=2$.

4 Numerical and computer simulation results

Several representative Figures are provided, illustrating the error performance of M-QAM in conjunction with EGC diversity over Nakagami/Rayleigh, Rice, Hoyt or Weibull fading channels. In each Figure, numerical and computer simulations results are presented. The computer simulation results (star signs) are compared to the corresponding mathematical analysis (lines) to check the accuracy of the proposed approach. Over 10^6 samples are used for the generation of the fading envelopes.

Figure 1 depicts the error performance of 4-QAM, 16-QAM and 64-QAM in conjunction with EGC diversity operating over independent and identically distributed (i.i.d.) ($\bar{\gamma}_i=\bar{\gamma}_0$, $m_i=m$, $i=1, 2, 3, 4$) Nakagami-m fading channels with $m=2$. From this Figure, it is apparent that the diversity reception is an effective technique for combatting the detrimental effects of deep fades experienced in wireless channels. It is also obvious that increasing the diversity order improves the error performance of the receiver, but this improvement does not increase proportionally with L. Figure 2 depicts the error performance of 32-QAM for dual branch EGC with equal branch SNRs in Nakagami-m fading as a function of the fading parameter, for several values of $\bar{\gamma}_0$. It is observed that the sensitivity of $\bar{P}_{se}$ to variations of m increases as $\bar{\gamma}_0$ increases.

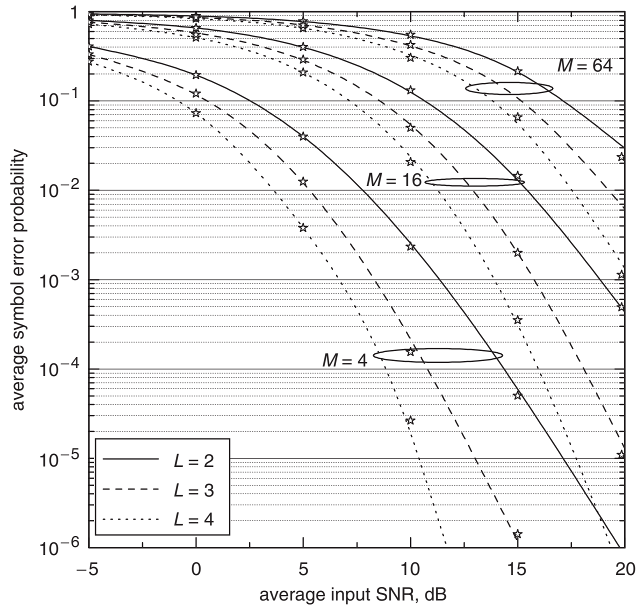

Fig. 1 *ASEP for M-QAM in EGC over Nakagami-m fading channels (m = 2)*

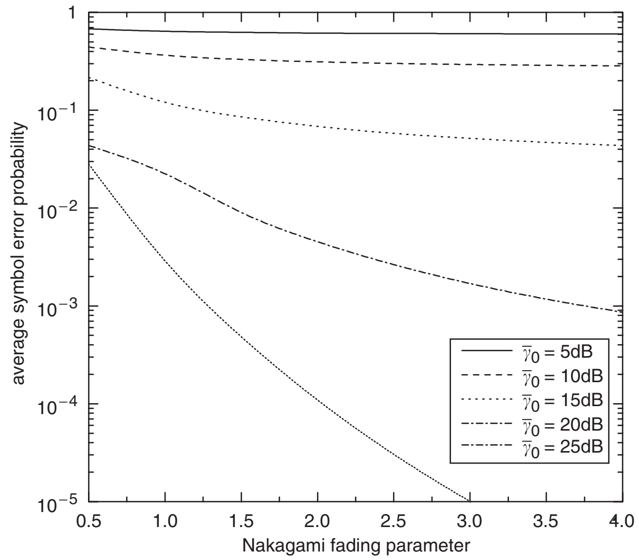

Fig. 2 *ASEP for 32-QAM against fading parameter m for dual EGC over Nakagami-m fading channels*

Figure 3 plots the ASEP for 4-QAM, 16-QAM and 64-QAM with dual and triple EGC diversity over i.i.d. Rice fading channels with $K_\ell=K=4$, while Fig. 4 depicts the ASEP for 4-QAM with dual and triple EGC diversity over i.i.d. Rice fading with $K=0$, 4 and 10. As expected, the ASEP performance is always better in channels where a strong line-of-sight exists (e.g. higher values of K). Notice that the relative diversity advantage is more pronounced in a poorer channel condition.

Figure 5 plots the ASEP for 4-QAM, 16-QAM and 64-QAM with dual and triple EGC diversity over identical Hoyt fading channels with $q_\ell=q=0.5$, and Fig. 6 plots the

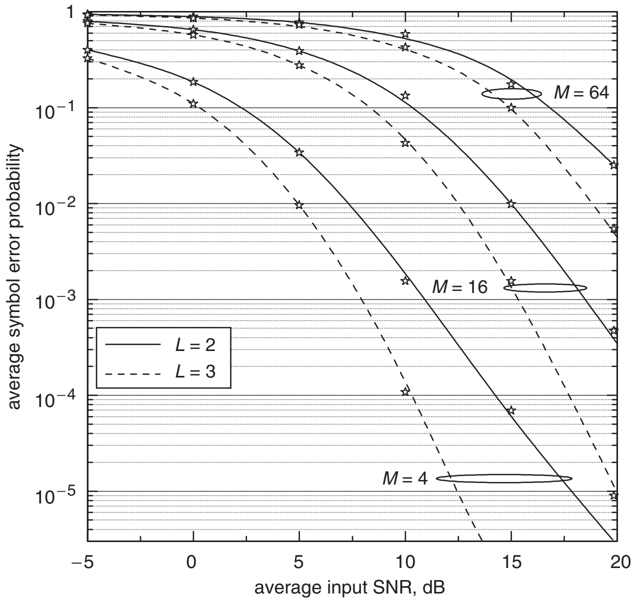

Fig. 3 *ASEP for M-QAM in EGC over Rice fading channels (K=4)*

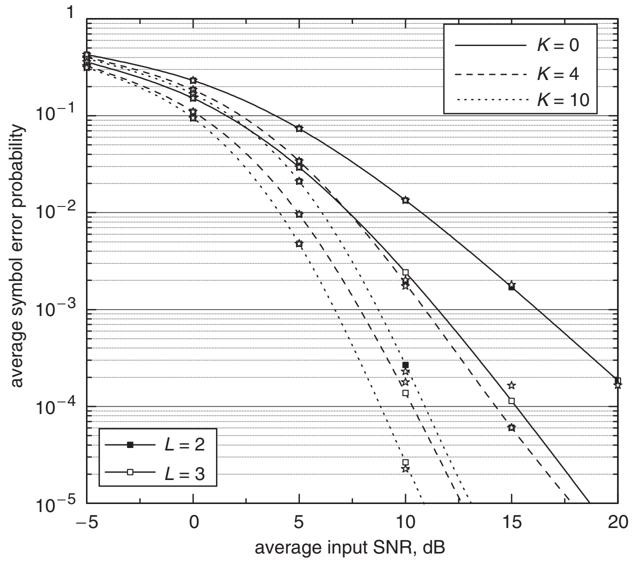

Fig. 4 *ASEP for 4-QAM in EGC over Rice fading channels*

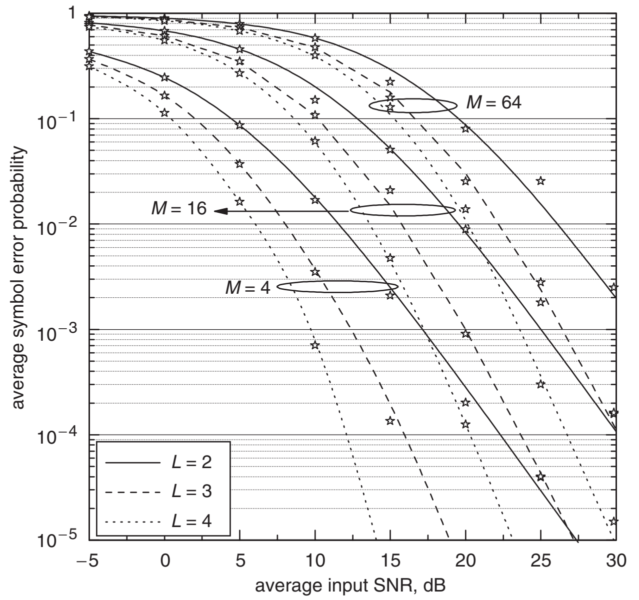

Fig. 5 *ASEP for M-QAM in EGC over Hoyt fading channels (q=0.5)*

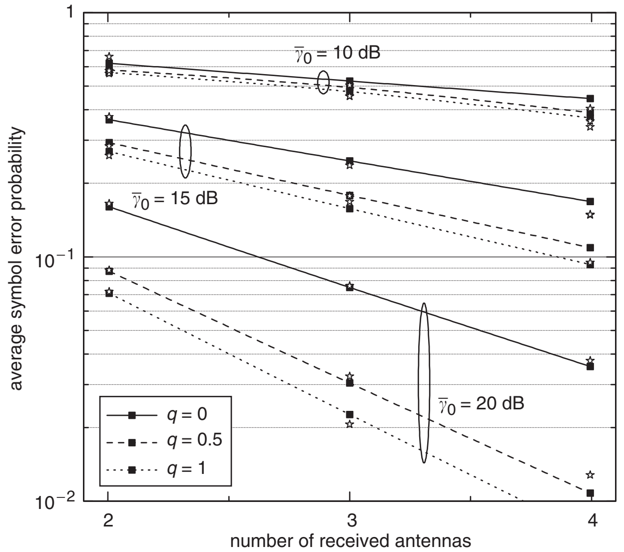

Fig. 6 *ASEP against order of diversity for 64-QAM with EGC over Hoyt fading channels*

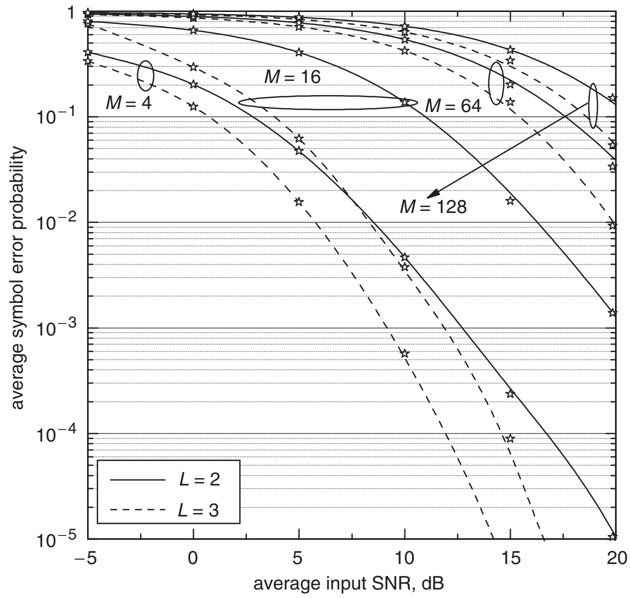

Fig. 7 *ASEP for M-QAM in EGC over Weibull fading channels (β=2.7)*

ASEP for 64-QAM in EGC against the order of diversity for several values of q and $\overline{\gamma}_0$. As also observed in Figs. 1–4, the ASEP for M-QAM in EGC for Hoyt fading improves with an increase of L, q, and/or $\overline{\gamma}_0$.

Figure 7 depicts the ASEP for 4-QAM, 16-QAM, 64-QAM and 128-QAM with EGC diversity over i.i.d. Weibull fading channels for $L=2$ and 3 and $\beta_\ell=\beta=2.7$. Finally, Fig. 8 examines the sensitivity of the ASEP of M-QAM in the presence of unequal branch SNRs for the dual EGC receiver operating over Weibull fading channels with $\beta=2.7$. It is observed that a system with equal branch SNRs performs better than that with unequal branch SNRs, which is to be expected since in EGC all the diversity branches are treated equally. It is clear from the presented Figures that an excellent match between analytical and computer simulations results is observed.

5 Conclusions

An alternative unified approach to the error performance of M-QAM, in conjunction with EGC diversity receivers

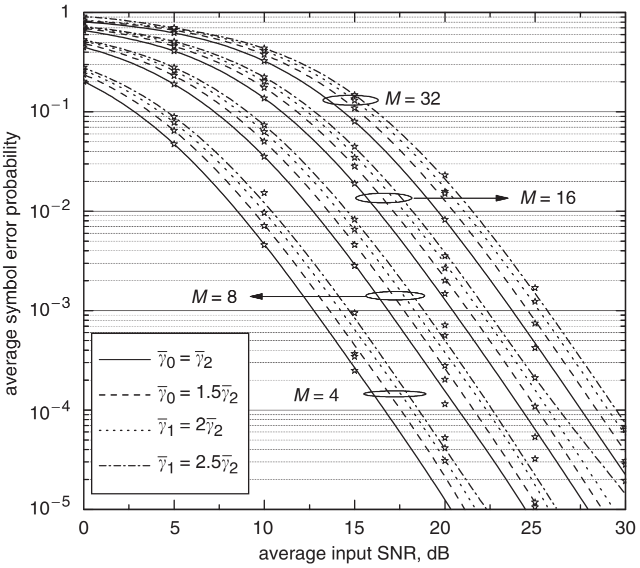

Fig. 8 *ASEP for M-QAM in dual EGC with unequal average branch SNRs in Weibull fading with ($\beta = 2.7$)*

operating over generalised fading channels, was presented. The moments of the EGC output SNR were extracted in closed form for several channel models and the corresponding MGFs were approximated with the use of Padé approximants theory. The proposed analysis is sufficiently general to handle arbitrary fading parameters as well as dissimilar signal strengths across the diversity branches.

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