Performance analysis of dual-diversity receivers over correlated generalised Gamma fading channels

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Abstract: The performance of dual-branch equal-gain combining (EGC) and maximal-ratio combining receivers operating over a composite correlated fading environment, modelled by the generalised Gamma (GG) distribution, is analysed. The moments of the output signal-to-noise ratio are derived in closed form for both types of receivers, and by employing the Padé approximants method, the average bit error probability is studied for a great variety of modulation schemes. Furthermore, based on the statistic of the product of two correlated GG random variables, a tight union upper bound for the outage probability of the EGC is obtained, whereas for the special case of Weibull fading a simpler bound is derived in closed form. The proposed mathematical analysis is complemented by various, numericaly evaluated performance results, whereas simulations verify the correctness of the proposed analysis.

1 Introduction

In general, it is widely accepted that radio propagation is characterised by three nearly independent phenomena: path loss variance with distance, shadowing (i.e. long-term fading) and multipath fading (i.e. short-term fading) [1]. Several experimental measurement campaigns have shown that multipath fading and shadowing occur simultaneously [2]. Thus, in order to study such fading environments, a composite fading model must be considered. Many statistical distributions are available in the technical literature for modelling composite fading channels, for example, Rayleigh-lognormal, Nakagami-lognormal [2] and more recently generalised-K [3, 4]. Another generic distribution which accurately describes the well-known channel models for both multipath and shadow fading is the generalised-Gamma (GG) [5]. The GG distribution is considered to be mathematically tractable when compared with the lognormal-based models. However, despite its usefulness, it has been applied in the context of wireless communications only recently [6] and since then has gained an increased interest [7–9].

In real life communication scenarios, the received signals subject to fading impairment may be independent or correlated. The latter results in a degradation of the diversity gain promised [10]. There are various useful works studying the performance of diversity receivers over independent [8, 11, 12] and correlated [9, 13, 14] GG fading channels. In [11], the performance of M-ary modulation schemes has been analysed for selection combining (SC), maximal ratio combining (MRC) and equal gain combining (EGC), whereas in [8], switch-and-stay combining over not necessarily identically distributed (id) GG fading channels has been studied. In [12], closed-form union bounds have been derived for the distribution of the sum of independent GG random variables (RVs) and have been applied to the performance analysis of EGC diversity receivers. The bivariate GG distribution with arbitrary fading parameters has been introduced and studied in [9, 13]. Moreover in [14], the multivariate GG distribution with exponential correlation has been introduced and applied to the performance analysis of SC receivers. However, the performance of dual-branch MRC and EGC diversity receivers operating over correlated GG fading channels has not been adequately addressed in the open technical literature and this is the topic of the current work.

In this paper, the moments of the output signal-to-noise ratio (SNR) of MRC and EGC diversity receivers, with not necessarily id fading channels, are derived. Capitalising on these expressions and by applying the Padé approximants method [15], the average bit error probability (ABEP) for several modulation schemes is studied for the diversity receivers under consideration. Furthermore, the probability density function (PDF) and the cumulative distribution function (CDF) of the product of two correlated GG RVs are derived. These expressions are useful to derive a tight union upper bound for the outage probability (OP) of the EGC diversity receiver. A corresponding bound for the special case of Weibull fading channel is also extracted in closed form.

This paper is organised as follows. After Introduction, in Section 2, the bivariate GG channel model is reviewed. In Section 3, the moments and the upper bounds for the CDF of the output SNR of EGC are derived. In Section 4, the previously derived results are applied to the performance analysis of MRC and EGC diversity receivers, whereas in Section 5, several numerically evaluated performance and computer simulation results are presented and discussed. Finally, concluding remarks are provided in Section 6.

2 Channel model

Let us consider a dual-branch diversity receiver operating in a correlated fading environment modelled by the bivariate

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GG distribution. The equivalent complex baseband received signal at the ℓth ($\ell = 1, 2$) input branch is $z_\ell = qR_\ell + n_\ell$, where q is the transmitted complex symbol with energy $E_s = \mathbb{E}\langle|q|^2\rangle$ ($\mathbb{E}\langle\cdot\rangle$ denotes expectation), n_ℓ the complex additive white Gaussian noise having single-sided power spectral density N_0 and R_ℓ the fading channel envelope modelled here as a GG RV. The usual assumptions for ideal synchronisation and perfect channels state information at the receiver are made. The joint PDF of R_1 and R_2 is given by [13, Equation (2)]

$$f_{R_1,R_2}(r_1, r_2) = \beta_1\beta_2(1-\rho)^{m_2} \times \sum_{k=0}^{\infty} \frac{(m_1)_k \rho^k}{k!(1-\rho)^{m_1+m_2+2k}} \left(\frac{m_1}{\Omega_1}\right)^{m_1+k} \times \left(\frac{m_2}{\Omega_2}\right)^{m_2+k} \frac{r_1^{\beta_1(m_1+k)-1}}{\Gamma(m_1+k)} \frac{r_2^{\beta_2(m_2+k)-1}}{\Gamma(m_2+k)} \times \exp\left[-\frac{1}{1-\rho}\left(\frac{m_1 r_1^{\beta_1}}{\Omega_1} + \frac{m_2 r_2^{\beta_2}}{\Omega_2}\right)\right] \times {}_1F_1\left[m_2 - m_1; m_2 + k; \frac{\rho m_2 r_2^{\beta_2}}{\Omega_2(1-\rho)}\right] \quad (1)$$

where $\beta_\ell \geq 0$ and $m_\ell \geq 1/2$ are the two shaping parameters related to the fading severity, $\Gamma(\cdot)$ the Gamma function [16, (8.310/1)], $(\cdot)_n$ the Pochhammer's symbol [16, Equation (9.749)], ${}_1F_1\,(\cdot; \cdot; \cdot)$ the confluent hypergeometric function [16, Equation (9.21)] and Ω_ℓ a parameter related to the average fading power as $\mathbb{E}\langle R_\ell^2\rangle = (\Omega_\ell/m_\ell)^{2/\beta_\ell}\Gamma(m_\ell + 2/\beta_\ell)/\Gamma(m_\ell)$. Also, ρ is the correlation coefficient of the underlying Nakagami-m random processes [13, Equation (9)] (As it is known, R_1 and R_2 can be generated by two Nakagami-m RV W_1 and W_2, having power correlation coefficient ρ, as $R_\ell = W_\ell^{2/\beta_\ell}$).

Setting different values to m_ℓ and β_ℓ, (1) simplifies to several important bivariate distributions for fading channel modelling. For example, for $\beta_\ell = 2$ and $m_\ell = 1$, it becomes Rayleigh, for $\beta_\ell = 2$, it becomes Nakagami-m and for $m_\ell = 1$, it becomes Weibull. Moreover, as $\beta_\ell \to 0$ and $m_\ell \to \infty$, (1) approaches the well-known lognormal joint PDF.

3 Statistics of the output SNR

In this section, closed-form expressions for the moments of the output SNR of MRC and EGC receivers operating over correlated GG fading channels, with not necessarily id fading channels, are derived. Furthermore, a tight upper bound is derived for the CDF of the output SNR of an EGC diversity receiver.

3.1 Moments

The instantaneous output SNR per symbol of EGC and MRC receivers can be written as

$$\gamma_{\text{out}} = \phi_{\delta,1}\frac{E_s}{N_0}\left(\sum_{i=1}^{2} R_i^{-\delta+2}\right)^{\delta+1} \quad (2)$$

where $\phi_{\delta,n} = (2^{-n} - 1)\,\delta + 1$ ($n > 0$), with $\delta = 0$ for MRC and $\delta = 1$ for EGC. The nth-order moment of γ_{out} can be obtained by averaging γ_{out}^n, that is, $\mu_n = \mathbb{E}\langle\gamma_{\text{out}}^n\rangle$, yielding

$$\mu_n = \phi_{\delta,n}\left(\frac{E_s}{N_0}\right)^n \mathbb{E}\left\langle\left(R_1^{-\delta+2} + R_2^{-\delta+2}\right)^{n(\delta+1)}\right\rangle \quad (3)$$

Let us define the instantaneous SNR per symbol of the ℓth input branch as $\gamma_\ell = R_\ell^2 E_s/N_0$ and the corresponding average SNR $\overline{\gamma}_\ell = \mathbb{E}\langle R_\ell^2\rangle E_s/N_0 = (\Omega_\ell/m_\ell)^{2/\beta_\ell}(E_s/N_0)/\Delta_\ell$, where $\Delta_\ell = \Gamma(m_\ell)/\Gamma(m_\ell + 2/\beta_\ell)$. It is well known that the nth power of a GG RV with parameters m_ℓ, β_ℓ and Ω_ℓ is also a GG RV with parameters m_ℓ, β_ℓ/n and Ω_ℓ [12]. Hence, γ_ℓ is a GG RV with parameters m_ℓ, $\beta_\ell/2$ and $(\Delta_\ell\overline{\gamma}_\ell)^{\beta_\ell/2}$. On the basis of this property, using the binomial identity [16, Equation (1.111)] in (3), and after performing some algebraic manipulations, μ_n can be expressed as

$$\mu_n = \phi_{\delta,n}\sum_{k=0}^{n(\delta+1)}\binom{n(\delta+1)}{k}\mathbb{E}\left\langle\gamma_1^{k/(\delta+1)}\gamma_2^{n-k/(\delta+1)}\right\rangle \quad (4)$$

Using the expression for the joint moments of γ_1 and γ_2 [13, Equation (8)], in (4) and after some mathematical simplifications, the nth-order moment of MRC and EGC output SNR, with not necessarily id fading channels, can be derived in closed form as

$$\mu_n = \phi_{\delta,n}\sum_{k=0}^{n(\delta+1)}\binom{n(\delta+1)}{k}\frac{(\Delta_1\overline{\gamma}_1)^{k/(\delta+1)}(\Delta_2\overline{\gamma}_2)^{n-k/(\delta+1)}}{\Gamma(m_1)\Gamma(m_2)} \times \Gamma\left[m_1 + \frac{2k}{\beta_1(\delta+1)}\right]\Gamma\left[m_2 + 2\frac{n(\delta+1)-k}{\beta_2(\delta+1)}\right] \times {}_2F_1\left[-\frac{2k}{\beta_1(\delta+1)}, -2\frac{n(\delta+1)-k}{\beta_2(\delta+1)}; m_2; \rho\right] \quad (5)$$

where ${}_2F_1(\cdot, ; \cdot)$ is the Gauss hypergeometric function [16, Equation (9.100)]. For the uncorrelated case, that is, $\rho = 0$, (5) becomes identical to a previously known result [12, Equation (25)].

3.2 Union bounds for the CDF of the output SNR of EGC

Considering identical shaping parameters to all branches, that is, $\beta_1 = \beta_2 = \beta$ and $m_1 = m_1 = m$, a union bound for the CDF of EGC output SNR operating over correlated GG fading channels is derived as an infinite series representation. Furthermore, a corresponding closed-form expression for Weibull fading channel is also provided.

3.2.1 GG channel model: Let $\mathcal{R}$ be a RV defined as $\mathcal{R} \triangleq R_1R_2$. By using [13, Equation (6)] and $\mathcal{R}$ in [17, Equation (6.74)], making a change of variables, using [16, Equation (3.471/9)], and after some straightforward mathematical manipulations, the PDF of $\mathcal{R}$ can be obtained in closed form as

$$f_{\mathcal{R}}(x) = \frac{2\beta m^{m+1}x^{\beta(m+1)/2-1}}{(1-\rho)\rho^{(m-1)/2}\Gamma(m)(\Omega_1\Omega_2)^{(m+1)/2}} \times I_{m-1}\left(\frac{2m}{1-\rho}\sqrt{\frac{\rho}{\Omega_1\Omega_2}}x^{\beta/2}\right)K_0\left(\frac{2m}{1-\rho}\frac{x^{\beta/2}}{\sqrt{\Omega_1\Omega_2}}\right) \quad (6)$$

where $I_{m-1}(\cdot)\,(\cdot)$ is the $(m-1)$th-order modified Bessel of the first kind [16, Equation (8.406)] and $K_n(\cdot)$ is the nth-order modified Bessel of the second kind [16, Equation (8.407)]. By setting $\beta = 2$, (6) becomes equal to a previously derived result [18, Equation (144)].

By integrating (6) with respect to x and after making a standard change of variables, an integral of the form $\mathcal{I} = \int_0^A x^m I_{m-1}(Bx)K_0(Cx)\,\mathrm{d}x$ needs to be solved, with A,

$B, C > 0$. This integral is very difficult, if not impossible, to be solved in closed form. An alternative and mathematically more tractable solution is to employ the infinite series representation for the modified Bessel function of the first kind [16, Equation (8.445)]. Following this approach, using [19, Equation (03.04.21.0009.01)] and after some mathematical manipulations, the CDF of $\mathcal{R}$ can be obtained as

$$F_{\mathcal{R}}(x) = \sum_{k=0}^{\infty} \frac{2\rho^k m^{2(k+m)} x^{\beta(k+m)}}{(1-\rho)^{2k+m}\Gamma(m)\Gamma(m+k)k!(k+m)(\Omega_1\Omega_2)^{k+m}} \times \left\{ {}_1F_2\left[1; k+m+1, k+m; \frac{m^2 x^\beta}{(1-\rho)^2\Omega_1\Omega_2}\right] \times K_0\left[\frac{2mx^{\beta/2}}{(1-\rho)\sqrt{\Omega_1\Omega_2}}\right] + {}_1F_2\left[1; k+m+1, k+m+1; \frac{m^2 x^\beta}{(1-\rho)^2\Omega_1\Omega_2}\right] \times \frac{mx^{\beta/2}}{(k+m)(1-\rho)\sqrt{\Omega_1\Omega_2}} K_1\left[\frac{2mx^{\beta/2}}{(1-\rho)\sqrt{\Omega_1\Omega_2}}\right]\right\} \quad (7)$$

where ${}_pF_q(\cdot)$ represents the generalised hypergeometric function with p, q integers [16, Equation (9.14/1)].

Let us define another RV $\mathcal{S} \triangleq R_1 + R_2$. Using the inequality between the arithmetic, $\mathcal{A} = (R_1 + R_2)/2$, and geometric, $\mathcal{G} = (R_1R_2)^{1/2}$, means, given by $\mathcal{A} \geq \mathcal{G}$ [20, Equation (3.2.1)], $\mathcal{S}$ can be lower bounded as $\mathcal{S} \geq 2\sqrt{\mathcal{R}}$. Hence, using (2) (for $\delta = 1$), γ_{egc} can be lower bounded as $\gamma_{egc} \geq 2\mathcal{R}$. Using (7) and after performing standard RVs transformations, the CDF of the EGC receiver output SNR can be upper bounded as

$$F_{\gamma_{egc}}(\gamma) \leq \sum_{k=0}^{\infty} \frac{2\xi^{2(k+m)}\rho^k(1-\rho)^m(\gamma/2)^{\beta(k+m)}}{\Gamma(m)\Gamma(m+k+1)k!} \times \left\{ {}_1F_2\left[1; k+m+1, k+m; \xi^2(\gamma/2)^\beta\right] \times K_0\left[2\xi(\gamma/2)^{\beta/2}\right] + {}_1F_2\left[1; k+m+1, k+m+1; \xi^2(\gamma/2)^\beta\right] \times \frac{\xi(\gamma/2)^{\beta/2}}{k+m} K_1\left[2\xi(\gamma/2)^{\beta/2}\right]\right\} \quad (8)$$

with $\Delta = \Gamma(m)/\Gamma(m + 2/\beta)$ and $\xi = (\Delta\sqrt{\overline{\gamma}_1\overline{\gamma}_2})^{-\beta/2}/(1-\rho)$.

3.2.2 Weibull channel model: By letting $m = 1$, that is, assuming Weibull fading, (6) simplifies to

$$f_{\mathcal{R}}(y) = \frac{2\beta y^{\beta-1}}{\Omega_1\Omega_2(1-\rho)} I_0\left[\frac{2\sqrt{\rho}y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right] \times K_0\left[\frac{2y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right] \quad (9)$$

By integrating (9) from zero to y, applying the transformation $w = y^{\beta/2}$, and using [16, Equation (5.54/1)], a closed-form expression for the CDF of $\mathcal{R}$ yields

$$F_{\mathcal{R}}(y) = \frac{2y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)} \left\{ I_0\left[\frac{2\sqrt{\rho}y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right] \times K_1\left[\frac{2y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right] + \sqrt{\rho} I_1\left[\frac{2\sqrt{\rho}y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right] \times K_0\left[\frac{2y^{\beta/2}}{\sqrt{\Omega_1\Omega_2}(1-\rho)}\right]\right\} \quad (10)$$

By following a procedure similar to that for deriving (8), the CDF of EGC operating over correlated Weibull fading channels can be upper bounded as follows

$$F_{\gamma_{egc}}(\gamma) \leq \zeta(\gamma/2)^{\beta/2}\{I_0[\zeta\sqrt{\rho}(\gamma/2)^{\beta/2}]K_1[\zeta(\gamma/2)^{\beta/2}] + \sqrt{\rho}I_1[\zeta\sqrt{\rho}(\gamma/2)^{\beta/2}]K_0[\zeta(\gamma/2)^{\beta/2}]\} \quad (11)$$

with $\zeta = 2[\Gamma(1+2/\beta)\sqrt{\overline{\gamma}_1\overline{\gamma}_2}]^{-\beta}/(1-\rho)$. Note that for $\beta = 2$ and $\rho = 0$, (11) agrees with a previously derived result [21, Equation (20)].

4 Performance analysis

In this section, several performance criteria of MRC and EGC diversity receivers operating over correlated GG fading channels are studied.

4.1 Amount of fading

The amount of fading (AoF), defined as $A_f \triangleq \mathrm{var}(\gamma_{out})/\overline{\gamma}_{out}^2$ out, is a unified measure of the severity of the fading channel and gives an insight into the performance of the entire system [2]. It can be expressed in closed form in terms of first- and second-order moments of γ_{out} as $A_f = \mu_2/\mu_1^2 - 1$. Using (5), the AoF at the output of both EGC and MRC receivers can be obtained.

4.2 Outage probability

The OP at the output of EGC is given as the probability that the output SNR falls below a predetermined threshold γ_{th}. This probability can be obtained by simply replacing γ with γ_{th} in the previously derived expressions for the upper bounds, that is, (8) for GG fading channels and (11) for Weibull fading channels, as

$$P_{out}(\gamma_{th}) = F_{\gamma_{egc}}(\gamma_{th}) \quad (12)$$

4.3 Average bit error probability

One very convenient approach to evaluate the ABEP of several modulation formats of signals transmitted in generalised fading channels is to follow the moments-generating function (MGF)-based approach [2]. However, the required MGF of the output SNR for the receivers under consideration is not readily available (It should be noted that an analytical solution of this MGF can be extracted. However, its form is computationally inefficient as it includes infinite series of Meijer's G-functions.). An alternative and also efficient method to approximate the MGF, and consequently evaluate the ABEP, is the so-called Padé approximants [22], which has been used in the past in various scientific fields, for example, to approximate PDFs [23] and in wireless communications [15, 24]. A Padé approximant is that rational function (of a specified order)

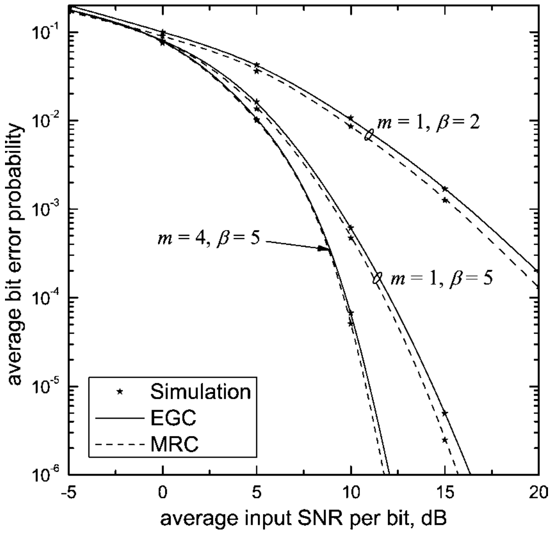

Fig. 1 *MRC and EGC diversity employing Gray-encoded square 16-QAM signalling: ABEP against the first-branch average input SNR per bit and for $\rho = 0.5$*

whose power series expansion agrees with a given power series to the highest possible order.

The MGF of the output SNR per symbol of EGC and MRC receivers, that is, $\mathcal{M}_{\gamma_{out}}(s) = \mathbb{E}\langle \exp(-s\gamma_{out})\rangle$, can be represented as a formal power series, for example, Taylor, yielding

$$\mathcal{M}_{\gamma_{out}}(s) = \sum_{n=0}^{\infty} \frac{\mu_n}{n!} s^n \quad (13)$$

Although, in general, μ_n given by (5) is in closed form, the above infinite series does not always converge or a very high number of moments is required. The main advantage of the Padé method is that an infinite series such as that in (13) can be approximated by a rational expression of finite low-order N_1 and $N_2 > N_1$ polynomials for the nominator and denominator, respectively. Hence, the main advandage of the Padé method is that only the first $(N_1 + N_2)$ order moments are required for approximating (13). In our research, we consider sub-diagonals Padé approximants, that is, $(N_2 = N_1 + 1)$, since it is only for

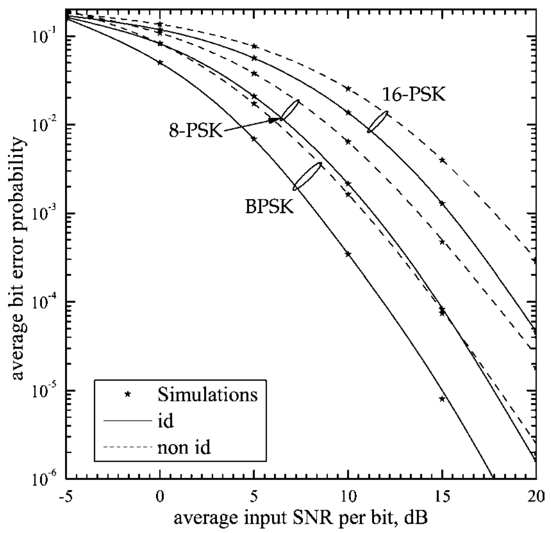

Fig. 2 *EGC diversity employing Gray-encoded square M-PSK signalling: ABEP against the first-branch average input SNR per bit for $\rho = 0.5$ and $m = 2$*

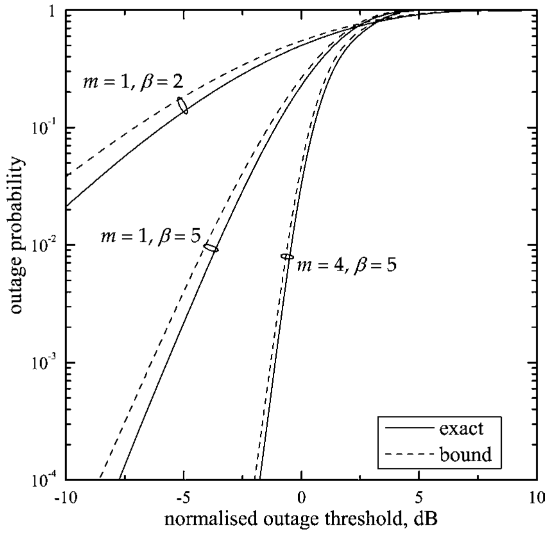

Fig. 3 *EGC diversity over GG fading: OP against the normalised outage threshold for $\rho = 0.5$ and several values of β and m*

such order of approximants that the convergence rate and the uniqueness can be assured [15, 22]. Hence, by obtaining accurate approximate rational expressions for $\mathcal{M}_{\gamma_{out}}(s)$ and using the MGF-based approach, the ABEP of EGC and MRC can be numerically evaluated.

5 Performance evaluation results and discussion

In this section, numerically evaluated performance results complemented by the equivalent computer simulation ones are presented and discussed. These results include performance comparisons of dual-branch MRC and EGC receiver structures, employing various modulation formats and different GG channel channels. As per our previous performance analysis, the following performance criteria will be used: ABEP [(5) and (13)], and OP [(8), (11) and (12)]. From now on, when non-id fading channels are considered, it is assumed that $\overline{\gamma}_2 = \overline{\gamma}_1/\sqrt{e}$, similar to [25].

In Figs. 1 and 2, the ABEP is plotted as a function of the average input SNR per bit of the first branch, that is, $\overline{\gamma}_b = \overline{\gamma}_1/\log_2(M)$. In Fig. 1, the ABEP performance of MRC and EGC is plotted for Gray-encoded square 16-quadrature amplitude modulation (QAM), with $\rho = 0.5$

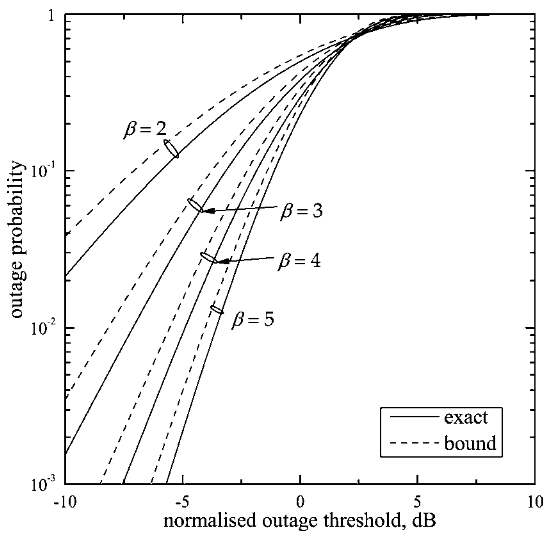

Fig. 4 *EGC diversity over Weibull fading: OP against the normalised outage threshold for $\rho = 0.5$ and several values of β*

and different values of m and β. It is illustrated that the ABEP improves with an increase of γ_b and/or β and/or m. Note that for $m = 1$ and $\beta = 2$ Rayleigh fading is assumed, while for $m = 4$ and $\beta = 5$ the fading severity is limited. In Fig. 2, the ABEP of EGC is plotted for Gray-encoded M-ary-phase-shift keying (PSK) ($M = 2$, 8 and 16), for $\rho = 0.5$ and $m = 2$. Moreover, for the case of id fading channels, it is assumed that $\beta_\ell = 2$, while for non-id, $\beta_1 = 2$ and $\beta_2 = 1.5$. As expected, binary PSK has always the best performance, whereas 16-PSK the worst. Furthermore, by considering id fading channels, the ABEP significantly improves. For comparison purposes, computer simulation results are also included in Figs. 1 and 2, verifying the accuracy of the proposed theoretical analysis.

In Figs. 3 and 4, the union upper bounds for the OP of an EGC receiver are plotted as a function of the normalised outage threshold and for id fading channels. Moreover, in order to verify the tightness of the proposed bounds, curves for the exact OP obtained by means of computer simulations are also included. In Fig. 3, the generic case of GG fading channel is considered with $\rho = 0.5$ and different values of β and m. It can be easily observed that as β and/or m increase, that is, the severity of the fading decreases, the OP decreases, whereas the differences between bound and simulation curves lessen. Finally, in Fig. 4, the special case of Weibull fading channel is considered with $\rho = 0.5$ and different values of the shaping parameter β. Once again by increasing β, the OP decreases. In both cases, it can be easily observed that the bounds are very close to the exact simulation ones.

6 Conclusions

We analysed the performance of dual-branch EGC and MRC diversity receivers operating over correlated GG fading channel. First, closed-form expressions for the moments of the output SNR were derived and then, following the MGF-based approach, used to study the ABEP of EGC and MRC. Furthermore, a tight upper bound for the CDF of the output SNR of the EGC receiver operating over GG fading channels was obtained, whereas for the special case of Weibull fading, a mathematically simpler bound was extracted in closed form. Several numerically evaluated results were presented, and simulations were also performed to verify the correctness and accuracy of the proposed analysis.

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