Performance of Diversity Receivers over Non-Identical Weibull Fading Channels

Nikos C. Sagias*, George K. Karagiannidis†, Dimitris A. Zogas‡, P. Takis Mathiopoulos†, Stavros A. Kotsopoulos‡ and George S. Tombras*

*Laboratory of Electronics, Physics Department, University of Athens, Panepistimiopolis, 15784, Athens, Hellas
Email: nsagias@space.noa.gr, gtombras@cc.uoa.gr
†Institute for Space Applications and Remote Sensing, National Observatory of Athens, Metaxa & Vas. Pavlou Street, Palea Penteli, 15236, Athens, Hellas
Email: {gkarag,mathio}@space.noa.gr
‡Electrical & Computer, Engineering Department, University of Patras, Rion, 26442, Patras, Hellas
Email: zogas@space.noa.gr, kotsop@ee.upatras.gr

***Abstract*— The performance of L-branch equal-gain combining (EGC) and maximal-ratio combining (MRC) receivers operating over correlative, non-identical Weibull fading channels is studied. Closed-form expressions are derived for the moments of the signal-to-noise ratio (SNR) at the output of the combiner and important performance criteria, such as average output SNR, amount of fading (AoF) and spectral efficiency (SE) at the low power regime, are extracted. We also evaluate the outage and average symbol error probability (ASEP) for several coherent and non-coherent modulation schemes, using a closed-form expression for the moment generating function (mgf) of the output SNR for MRC receivers and the Padé approximation to the mgf for EGC receivers. The proposed mathematical analysis is complimented by various numerical and computer simulations results, which point out the effects of fading severity and correlation on the overall system's performance.**

I. Introduction

Diversity is an effective and widely used employed technique in contemporary digital communications receivers for mitigating the effects of multipath fading and improving the overall wireless system's performance. Maximal-ratio combining (MRC) and equal-gain combining (EGC) are two of the most popularly employing diversity techniques. The performance of EGC and MRC diversity receivers has been extensively studied in the open technical literature for several well-known fading statistical models, such as Rayleigh, Rice and Nakagami-m assuming independent or correlative fading (see [1]–[6] and references therein). However, another well-known fading channel model, namely the Weibull model, has not yet received as much attention as the others, despite the fact that it exhibits an excellent fit to experimental fading channel measurements, both for indoor [7], as well as for outdoor environments [8].

Recently, three contributions dealing with the performance analysis of diversity receivers over Weibull fading channels were presented by Sagias *et al.* [9]–[11]. In [9], the performance of switched diversity receivers in Weibull fading was studied. In [10], dual branch selection combining (SC) receivers in correlated Weibull fading were considered and in [11], important performance measures such as the outage probability and the average output signal-to-noise ratio (SNR) were studied, for L-branch SC receivers operating over independent and identically distributed (i.i.d.) Weibull fading channels. However ,to the best of the authors' knowledge, the performance analysis of MRC and EGC receivers is not readily available in the open technical literature.

In this paper, a moments-based approach to the performance analysis of L-branch EGC and MRC receivers, operating in independent or correlated, not necessarily identically distributed (id.d.), Weibull fading is presented. For both EGC and MRC receivers useful expressions for the moments of the output SNR are obtained in closed-form. An accurate approximate expression is derived for the moment generating function (mgf) of the output SNR of the EGC receiver utilizing the Padé approximants theory [12], while a novel closed-form expression for the corresponding mgf of the MRC, is obtained. Important performance criteria such as average output SNR, amount of fading (AoF) and spectral efficiency (SE) at the low power regime, are extracted in closed-forms, using the moments of the output SNR both for independent and correlative fading. Moreover, using the well-known mgf approach [1], the outage and the average symbol error probability (ASEP) for several coherent, non-coherent binary and multilevel modulation schemes, are studied. The proposed mathematical analysis is illustrated by various selected numerical results and validated by computer simulations.

II. System and Channel Model

An L-branch diversity receiver operating in a flat fading environment is considered. The baseband received signal at the ℓth, $\ell = 1, 2, \ldots, L$, diversity branch is $z_\ell = s\, a_\ell + n_\ell$, where s is the transmitted symbol, a_ℓ is the fading envelope and n_ℓ is the additive white Gaussian noise (AWGN) with a single-sided power spectral density N_0. The noise components are assumed to be statistically independent of the signal and uncorrelated with each other.

We assume that a_ℓ is a two parameter Weibull random variable (rv), with probability density function (pdf) given by

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[13]

$$f_{a_\ell}(a_\ell) = \frac{\beta}{\omega_\ell}\left(\frac{a_\ell}{\omega_\ell}\right)^{\beta-1} e^{-\left(\frac{a_\ell}{\omega_\ell}\right)^\beta} \tag{1}$$

where β and ω_ℓ are the fading and scaling parameters of the distribution, respectively. The scaling parameter is related to the average power of fading as $\omega_\ell^2 = \overline{a_\ell^2}/\Gamma(d_2)$, where in general $d_\tau = 1+\tau/\beta$, τ is a real constant, $\Gamma(\cdot)$ is the Gamma function [14, eq. (6.1.1] and $\overline{a_\ell^2}$ is the average power of fading. Moreover, β is related to the fading severity and as β increases the severity of fading decreases, while for β=2, (1) reduces to the well-known Rayleigh pdf. The cumulative distribution function (cdf) and the moments of a_ℓ are given by

$$F_{a_\ell}(a_\ell) = 1 - e^{-\left(\frac{a_\ell}{\omega_\ell}\right)^\beta} \tag{2}$$

and

$$E\langle a_\ell^n\rangle = \omega_\ell^n\,\Gamma(d_n) \tag{3}$$

respectively, where n is a positive integer and $E\langle\cdot\rangle$ denotes expectation. The instantaneous output SNR of EGC or MRC receivers can be expressed as

$$\gamma_{out} = \lambda_{\xi,1}\frac{E_s}{N_0}\left(\sum_{i=1}^{L} a_i^{-\xi+2}\right)^{\xi+1} \tag{4}$$

where for MRC $\xi = 0$ and for EGC $\xi = 1$, with $\lambda_{\xi,n} = (L^{-n}-1)\,\xi + 1$ and $E_s = E\left\langle |s|^2\right\rangle$ is the transmitted symbols' energy.

Next, the necessary theoretical framework for the bivariate Weibull distribution, which will be used to study the performance of diversity receivers in correlative fading, will be briefly presented. The complementary cdf (or survival function) of the bivariate Weibull distribution and the covariance of a_1 and a_2 (joint moments of order $n+m$) are [15]

$$E\langle a_1^n, a_2^m\rangle = \omega_1^n\,\omega_2^m\,\frac{\Gamma(d_{n\delta})\,\Gamma(d_{m\delta})\,\Gamma(d_{n+m})}{\Gamma\left[d_{(n+m)\delta}\right]}. \tag{5}$$

and

$$\tilde{F}_{a_1,a_2}(a_1,a_2) = e^{-\left[\left(\frac{a_1}{\omega_1}\right)^{\frac{\beta}{\delta}}+\left(\frac{a_2}{\omega_2}\right)^{\frac{\beta}{\delta}}\right]^\delta} \tag{6}$$

respectively, where δ, $0 \le \delta \le 1$, is a parameter which is related to the correlation coefficient, defined $\rho = \operatorname{cov}(a_1,a_2)/\sqrt{\operatorname{var}(a_1)\operatorname{var}(a_2)}$, as

$$\rho = \frac{\Gamma^2(d_\delta)\,\Gamma(d_2) - \Gamma^2(d_1)\,\Gamma(d_{2\delta})}{\Gamma(d_{2\delta})\left[\Gamma(d_2)-\Gamma^2(d_1)\right]}\,. \tag{7}$$

By replacing (2) and (6) in [16, eq. (6.22)], the cdf of a_1 and a_2 can be derived as

$$\begin{aligned} F_{a_1,a_2}(a_1,a_2) =& 1 - e^{-\left(\frac{a_2}{\omega_2}\right)^\beta} - e^{-\left(\frac{a_1}{\omega_1}\right)^\beta} \\ &+ e^{-\left[\left(\frac{a_1}{\omega_1}\right)^{\frac{\beta}{\delta}}+\left(\frac{a_2}{\omega_2}\right)^{\frac{\beta}{\delta}}\right]^\delta}. \end{aligned} \tag{8}$$

For independent input paths, $\rho = 0$ (i.e., $\delta = 1$), (8) can be written as a product of two single Weibull cdfs and differentiating (8), the joint pdf of a_1 and a_2 can be extracted in a rather complicated form, but is not presented due to space limitations.

III. Moments of the Output SNR

By definition, using (4), the nth moment of the combiner's output SNR is defined as $\mu_n = E\langle\gamma_{out}^n\rangle$ and expanding the term $\left(\sum_{i=1}^{L} a_i^{-\xi+2}\right)^{n(\xi+1)}$, using the multinomial identity [14, eq. (24.1.2)], μ_n can be written in terms of the instantaneous input SNR $\gamma_\ell = a_\ell^2\,E_s/N_0$, as

$$\mu_n = \lambda_{\xi,n}\,[n(\xi+1)]!\sum_{\substack{k_1,\ldots,k_L=0\\ k_1+\ldots+k_L=n(\xi+1)}}^{n(\xi+1)}\frac{E\left\langle\gamma_1^{\frac{k_1}{\xi+1}}\cdots\gamma_L^{\frac{k_L}{\xi+1}}\right\rangle}{k_1!\ldots k_L!}. \tag{9}$$

For uncorrelated input paths, the mean product, in (9), can be written as a product of means, where each mean term can be obtained from (3) as

$$E\langle\gamma_\ell^n\rangle = \overline{\gamma}_\ell^n\,\Gamma(d_{2n})/\Gamma^n(d_2) \tag{10}$$

due to the fact that the instantaneous SNR follows also a Weibull pdf [13], where $\overline{\gamma}_\ell = \overline{a_\ell^2}\,E_s/N_0$ is the ℓth average input SNR. Thus, using (9) and (10), the moments of the EGC or MRC output SNR for independent but not necessarily id.d. input branches can be written in closed-form as

$$\begin{aligned}\mu_n =& \frac{\lambda_{\xi,n}}{\Gamma^n(d_2)}\,[n(\xi+1)]! \\ &\times\sum_{\substack{k_1,\ldots,k_L=0\\ k_1+\ldots+k_L=n(\xi+1)}}^{n(\xi+1)}\prod_{j=1}^{L}\frac{\Gamma\left(d_{\frac{2k_j}{\xi+1}}\right)}{k_j!}\,\overline{\gamma}_j^{\frac{k_j}{\xi+1}}.\end{aligned} \tag{11}$$

For dual diversity ($L = 2$) with correlated input paths, the term $E\left\langle\gamma_1^{k_1/(\xi+1)}\gamma_2^{k_2/(\xi+1)}\right\rangle$, appearing in (9), can be evaluated, using (5), as

$$E\langle\gamma_1^n\,\gamma_2^m\rangle = \overline{\gamma}_1^n\,\overline{\gamma}_2^m\,\frac{\Gamma(d_{2n\delta})\,\Gamma(d_{2m\delta})\,\Gamma\left[d_{2(n+m)}\right]}{\Gamma^{n+m}(d_2)\,\Gamma\left[d_{2(n+m)\delta}\right]} \tag{12}$$

and thus, the nth moment of the output SNR for dual EGC or MRC can be expressed from (9) with (12) in closed-form as

$$\begin{aligned}\mu_n =& \frac{2^{-\xi n}\Gamma(d_{2n})}{\Gamma^n(d_2)\,\Gamma^n(d_{2\delta n})} \\ &\times\sum_{k=0}^{n(\xi+1)}\overline{\gamma}_1^{\frac{k}{\xi+1}}\,\overline{\gamma}_2^{\,n-\frac{k}{\xi+1}}\binom{n(\xi+1)}{k}\Gamma\left(d_{\frac{2\delta k}{\xi+1}}\right)\Gamma\left[d_{2\delta\left(n-\frac{k}{\xi+1}\right)}\right].\end{aligned} \tag{13}$$

A. Average Output SNR

When the receiver employs MRC, the average output SNR $\overline{\gamma}_{MRC}$, can be easily obtained for both independent and correlative fading, by setting $\xi = 0$ and $n = 1$ in (9), leading to the well-known formula $\overline{\gamma}_{MRC} = \sum_{i=1}^{L}\overline{\gamma}_i$. In this case, the fading correlation does not affect the average output SNR performance.

For EGC with independent input branches, after straightforward mathematical manipulations, the average output SNR

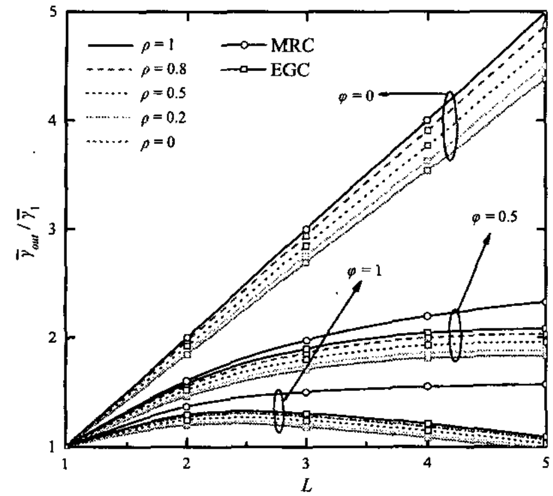

Fig. 1. First branch normalized average output SNR versus L of EGC and MRC with constant correlation, exponentially decaying pdp and $\beta = 2.5$.

can be derived in closed-form setting $n = \xi = 1$ in (11) as

$$\overline{\gamma}_{EGC} = \frac{1}{L}\left[\sum_{i=1}^{L}\overline{\gamma}_i + 2\frac{\Gamma^2(d_1)}{\Gamma(d_2)}\sum_{i=2}^{L}\sum_{j=1}^{i-1}\sqrt{\overline{\gamma}_i\overline{\gamma}_j}\right] \quad (14)$$

while for i.i.d. input paths (i.e., $\overline{\gamma}_\ell = \overline{\gamma}_0,\ \forall\ell$), (14) reduces to

$$\overline{\gamma}_{EGC} = \left[1 + (L-1)\,\Gamma^2(d_1)/\Gamma(d_2)\right]\overline{\gamma}_0. \quad (15)$$

For correlated input paths, the average output SNR of the EGC, $\overline{\gamma}_{EGC}$, can be obtained by setting $n = \xi = 1$ in (9), yielding

$$\overline{\gamma}_{EGC} = \frac{2}{L}\sum_{\substack{k_1,\ldots,k_L=0\\k_1+\ldots+k_L=2}}^{2}\frac{E\left\langle\gamma_1^{\frac{k_1}{2}}\ldots\gamma_L^{\frac{k_L}{2}}\right\rangle}{k_1!\ldots k_L!}. \quad (16)$$

Clearly, only the terms of the form $E\left\langle\sqrt{\gamma_i\gamma_j}\right\rangle$ need to be evaluated in (16). Therefore, using (12), the average output SNR of the L-branch EGC receiver over correlated Weibull fading channels can be expressed in a simple closed-form expression as

$$\overline{\gamma}_{EGC} = \frac{1}{L}\left[\sum_{i=1}^{L}\overline{\gamma}_i + 2\frac{\Gamma^2(d_\delta)}{\Gamma(d_{2\delta})}\sum_{i=2}^{L}\sum_{j=1}^{i-1}\sqrt{\overline{\gamma}_i\overline{\gamma}_j}\right]. \quad (17)$$

Note, that for $\delta = 1$ (17) reduces to (14). Furthermore, for id.d. input branches (17) simplifies to

$$\overline{\gamma}_{EGC} = \left[1 + (L-1)\,\Gamma^2(d_\delta)/\Gamma(d_{2\delta})\right]\overline{\gamma}_0. \quad (18)$$

Assuming constant correlation among the EGC and MRC branches and an exponentially decaying power delay profile (pdp) $\left(i.e.,\ \overline{\gamma}_\ell = \overline{\gamma}_1 e^{-\varphi(\ell-1)}\right)$, Figure 1 plots the first branch normalized average output SNR of EGC and MRC, as a function of L, for $\beta = 2.5$, various values of ρ and power decaying factor φ. In contrary to the behavior of the average SNR at the MRC output, which does not depend on ρ, the average output SNR of the EGC increases as ρ increases. Also, the combining loss of the receiver gets more accentuated as φ increases. Note, that by increasing ρ, using (13), it can be easily verified that, not only the normalized average output SNR increases, but also the variance of the output SNR.

B. Amount of Fading (AoF)

The AoF is a unified measure of the severity of fading, which is typically independent of the average fading power and can be expressed as [1]

$$\text{AoF} = \mu_2/\overline{\gamma}_{out}^2 - 1. \quad (19)$$

When the receiver employs MRC, the first two moments of the output SNR needed in (19), can be derived in closed-form for arbitrary number of correlated non-identical branches, using (9). Moreover, for EGC the AoF can be evaluated in closed-form for independent, non-identical input paths, using (11) and for dual diversity with correlative fading, using (13).

C. Spectral Efficiency (SE)

The AoF can be used to study the SE of a flat fading channel in the very noise (low power) region. In this region, the minimum bit energy E_b per noise level, required for reliable communication is $(E_b/N_0)_{\min} = -1.59$dB and the slope of the SE curve versus E_b/N_0 in b/s/Hz per 3 dB, at $(E_b/N_0)_{\min}$ is [17]

$$S_0 = \frac{2\,E^2\left\langle r^2\right\rangle}{E\left\langle r^4\right\rangle} = \frac{2\,\overline{\gamma}_{out}^2}{\mu_2} \quad (20)$$

with r being the combiner's output envelope. Using (19), a useful expression for the slope of the SE in the very noise region can be obtained as

$$S_0 = 2/\left(\text{AoF} + 1\right). \quad (21)$$

In Fig. 2, the SE in the high noise region for EGC and MRC, is plotted for $\beta = 2.5$ and several values of ρ and L. For comparison purposes, in the same figure, the SE of the AWGN channel is also plotted. Regardless of the number of branches and the fading correlation, the SE of the MRC is always higher than that of the EGC and both are lower than the corresponding curve for the AWGN channel.

IV. Error Rates and Outage Probability

Using the well-known mgf approach, the ASEP $\overline{P}_{se}$ for several coherent and non-coherent modulation schemes, is studied.

A. Average Symbol Error Probability (ASEP)

1) MRC: Using (1) and (3) the mgf of the output SNR of an MRC receiver, $\mathcal{M}_{\gamma_{MRC}}(s) = \prod_{i=1}^{L}\mathcal{M}_{\gamma_i}(s)$, where $\mathcal{M}_{\gamma_i}(s)$ is the mgf of the SNR of the ith input path, operating over independent Weibull fading channels can be written as

$$\mathcal{M}_{\gamma_{MRC}}(s) = \prod_{i=1}^{L}\frac{\beta}{2\left(a\overline{\gamma}_i\right)^{\frac{\beta}{2}}}\int_0^\infty \gamma_i^{\frac{\beta}{2}-1}\,e^{-s\gamma_i}\,e^{-\left(\frac{\gamma_i}{a\overline{\gamma}_i}\right)^{\frac{\beta}{2}}}\,d\gamma_i. \quad (22)$$

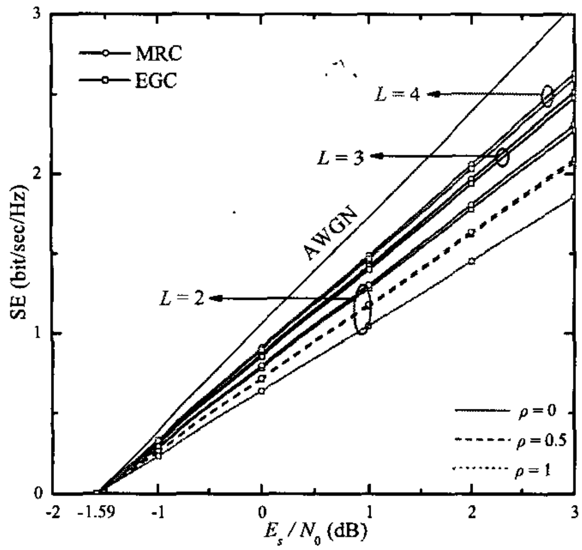

Fig. 2. Spectral efficiency in the low power regime for $\beta = 2.5$.

The above integral can be evaluated in closed-form as follows. By expressing the two exponential function as a Meijer's G-functions [18, eq. (9.301)], i.e., $e^{-g(x)} = G_{0,1}^{1,0}\left[g(x) \,\middle|\, \begin{smallmatrix} - \\ 0 \end{smallmatrix}\right]$ [19, eq. (11)], where $g(\cdot)$ is an arbitrary function, and using [19, eq. (21)], (22) can be expressed in closed-form as

$$\mathcal{M}_{\gamma_{MRC}}(s) = \frac{\beta}{2\,(a\overline{\gamma}_i)^{\frac{\beta}{2}}} \frac{\left(\frac{k}{l}\right)^{\frac{1}{2}} \left(\frac{l}{s}\right)^{\frac{\beta}{2}}}{(2\pi)^{\frac{k+l}{2}-1}} \times \prod_{i=1}^{L} G_{l,k}^{k,l}\left[\frac{(a\overline{\gamma}_i)^{-\frac{k\beta}{2}}}{s^l}\frac{l^l}{k^k} \,\middle|\, \begin{matrix} I(l,1-\frac{\beta}{2}) \\ I(k,0)\end{matrix}\right]. \quad (23)$$

In the above equation, $I(n,\xi) \triangleq \xi/n, (\xi+1)/n, \ldots, (\xi+n-1)/n$, with ξ an arbitrary real value, k and l are positive integers so that $l/k = \beta/2$. Depending upon the value of β, a set with minimum values of k and l can be properly chosen (e.g., for $\beta = 2.5$, $k = 4$ and $l = 5$ need to be chosen). Note, that for the special case of β integer, $k = 2$ and $l = \beta$.

2) EGC: Unfortunately, a useful expression for the mgf such (23), is not available for EGC receivers operating in Weibull fading. Therefore, we propose the use of Padé approximants [12] as an alternative and simple way to approximate the mgf and consequently to evaluate the ASEP for EGC receivers over Weibull fading channels. By definition, the mgf is given by $\mathcal{M}_{\gamma_{EGC}}(s) = E\langle e^{s\,\gamma_{EGC}}\rangle$ and can be represented as a formal power series (e.g., Taylor) as

$$\mathcal{M}_{\gamma_{EGC}}(s) = \sum_{n=0}^{\infty} \frac{1}{n!}\mu_n\, s^n. \quad (24)$$

Although the moments of all orders, μ_n, for the L-branch EGC can be evaluated in closed-forms, in practice, using the analysis of Section III, only a finite number should be used, truncating the series in (24). A Padé approximant to the mgf is that rational function of a specified order B for the denominator and A for the nominator, whose power series expansion agrees with the $(A+B)$-order power expansion of $\mathcal{M}_{\gamma_{EGC}}(s)$, i.e.,

$$_{A}R_{B}(s) = \frac{\sum_{i=0}^{A} c_i\, s^i}{1 + \sum_{i=1}^{B} b_i\, s^i} = \sum_{n=0}^{A+B} \frac{1}{n!}\mu_n\, s^n + O\left(s^{N+1}\right) \quad (25)$$

where $O\left(s^{N+1}\right)$ is the remainder after the truncation. Hence, the first $(A+B)$ moments are need to be evaluated in order to construct the approximant $_{A}R_{B}(s)$. In our analysis, $\mathcal{M}_{\gamma_{EGC}}(s)$ is approximated using sub-diagonals $(_{A}R_{A+1}(s))$ Padé approximants [12], [4].

Using the mgf expressions, either in closed-form, for MRC, or with the aid of Padé approximants, for EGC, the ASEP can be directly calculated for non-coherent and differential binary signaling (e.g., NBFSK and BDPSK) since for all other cases (e.g., BPSK, M-PSK, M-QAM, M-AM and M-DPSK) single integrals with finite limits and integrands composed of elementary (exponential and trigonometric) functions, have to be readily evaluated via numerical integration.

As indicative examples, Figs 3 and 4 plot the ASEP of BPSK and 16-QAM, respectively of EGC and MRC, versus the average SNR of the first branch, for id.d. input paths with $\beta = 2.5$ and for several values of ρ and L. As shown, the error performance of MRC is always better than that of EGC, while the diversity gain decreases for both combiners with the increase of the correlation, as expected. In the same figures, computer simulations results are also plotted for comparison purposes. An excellent match between analytical and computer simulations results is observed. Note, that although the normalized average output SNR of the EGC increases with ρ, as mentioned in Section III, the ASEP deteriorates. Thus, the average output SNR is not suitable performance criterion to study the performance of EGC in correlative fading.

B. Outage Probability

If γ_{th} is a certain specified threshold, then the outage probability is defined as the probability that the combiner's output SNR, γ_{out}, falls below γ_{th} and is given by [1]

$$P_{out} = F\gamma_{out}(\gamma_{th}) = \mathcal{L}^{-1}\left[\frac{\mathcal{M}_{\gamma_{out}}(s)}{s}\right]\Bigg|_{s=\gamma_{th}} \quad (26)$$

where $F\gamma_{out}(\gamma_{out})$ is the cdf of the combiner's output SNR, $\mathcal{L}^{-1}(\cdot)$ denotes the inverse Laplace transform and $\mathcal{M}_{\gamma_{out}}(s)$ is either $\mathcal{M}_{\gamma_{EGC}}(s)$ for EGC, or $\mathcal{M}_{\gamma_{MRC}}(s)$ for MRC.

For EGC, dividing the nominator with the denominator in (25), the Padé rational form of $\mathcal{M}_{\gamma_{EGC}}(s)$ can be easily written as a finite sum of fractions with single poles, i.e.,

$$M_{\gamma_{EGC}}(s) \cong \sum_{i=1}^{B} \frac{\lambda_i}{s+p_i} \quad (27)$$

where $\{p_i\}$ are the poles of the Padé approximants to the mgf, which must have negative real part and $\{\lambda_i\}$ are the

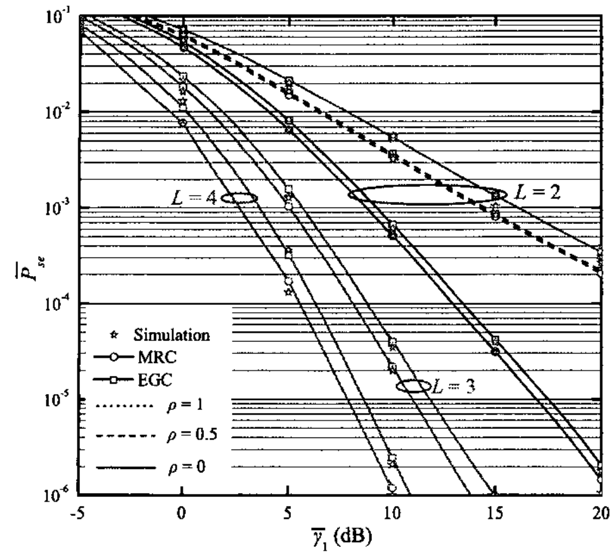

Fig. 3. ASEP of BPSK for EGC and MRC with $\beta = 2.5$.

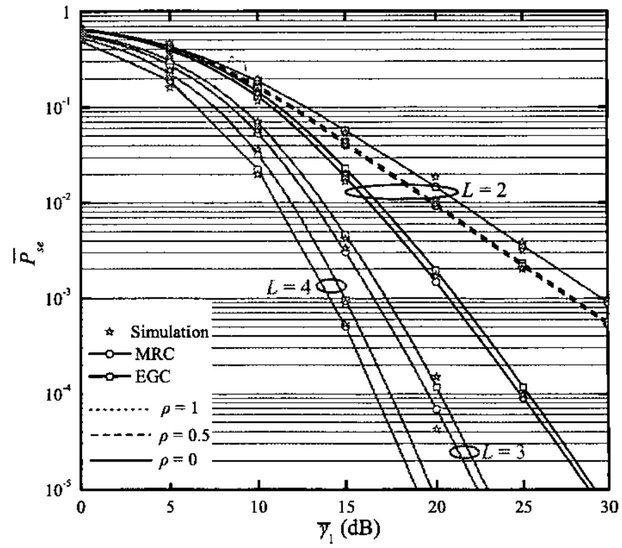

Fig. 4. ASEP of 16-QAM for EGC and MRC with $\beta = 2.5$.

residues. Using the residue inversion formula, P_{out} can be easily evaluated from (26) in closed-form as

$$P_{out} = \sum_{i=1}^{B} \frac{\lambda_i}{p_i} e^{-p_i \gamma_{th}}. \qquad (28)$$

For MRC, due to the complicated form of $\mathcal{M}_{\gamma_{MRC}}(s)$, P_{out} can be evaluated using an accurate algorithm for numerically inverting Laplace transforms, summarized in [20]. However, this algorithm does not presented here due to space limitations.

V. Conclusions

The analysis of L-branch MRC and EGC receivers' performance, operating over Weibull fading channels, was presented. Accurate expressions were derived for the mgf of the output SNR for EGC utilizing the Padé approximants theory, while a closed-form expression for the corresponding mgf of the MRC was obtained. For both EGC and MRC receivers the moments of the output SNR were obtained in closed-form. Important performance criteria, such as average output SNR, AoF, SE at the low power regime, outage probability and ASEP were studied. It was also found that, the normalized average output SNR is not the appropriate metric to study the EGC performance in correlative fading.

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