Performance of a L-Branch Predetection EGC Receiver over Independent Hoyt Fading Channels for M-ary Coherent and Noncoherent Modulations using PDF-Based Approach

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***Abstract*—Performance of a L-branch predetection equal gain combining receiver has been analyzed in independent Hoyt fading channels with arbitrary fading parameters applying classical probability density function (PDF) based approach. An approximate but highly accurate PDF of the sum of independent Hoyt random variables has been used for the analysis. Simple and easy to evaluate expressions for the outage probability and amount of fading have been obtained. An expression for average symbol error rate, in the form of an infinite series with a single integral with finite limits has been obtained which is applicable for a number of M-ary coherent and noncoherent modulations. Numerically evaluated results have been compared with the published results to verify the correctness of the derived expressions.**

Index Terms- Diversity, Hoyt fading, equal gain combining, average symbol error rate, PDF.

I. Introduction

Performance of a predetection equal gain combining (EGC) diversity receiver in fading channels is known to be close to the performance of the optimum maximal ratio combining (MRC) receiver, with relatively less implementation complexity [1]. The performance analysis of a L-branch predetection EGC receiver is not easy compared to MRC. The reason is due to the age old problem of obtaining the probability density function (PDF) of the sum of L fading envelopes, which is not known in closed-form for $L \geq 3$ [2]. This void eliminates the possibility of applying the direct and simple PDF-based approach [1] to the performance analysis of a predetection EGC receiver beyond $L = 2$. Over the years, in an effort to obtain the performance for $L \geq 3$, the researchers have developed a number of alternative approaches such as characteristic function (CF), Parseval's theorem method, Padé approximation etc. [2]-[6]. Recently, with an aim to generalize and obtain a better fit for the experimental data, several new fading distributions such as the κ-μ, η-κ and η-μ have been proposed [7]-[9]. Interestingly, in [7] an approximate but highly accurate PDF of the sum of independent Hoyt random variables (RVs) has been presented using moment based estimators. This useful result can be readily applied to analyze the performance of a L-branch predetection EGC receiver in independent Hoyt fading channels using PDF-based approach.

In this paper, we analyze the performance of a L-branch predetection EGC receiver in independent Hoyt fading channels with arbitrary fading parameters. Analytical expressions for the outage probability and amount of fading (AF) and average symbol error rate (ASER) for M-ary, coherent and non-coherent modulation schemes have been obtained.

The paper is organized as follows. In Section II, we introduce the channel and the receiver system model. The performance analysis has been presented in Section III. In Section IV, the numerical evaluation steps have been discussed. Results and discussion have been presented in Section V. Finally, we conclude the paper in Section VI.

II. Channel and Receiver

The channel has been assumed to be slow, frequency non-selective, with Hoyt fading statistics. The complex low-pass equivalent of the signal received at the l^{th} input branch ($1 \leq l \leq L$) over one symbol duration T_s can be expressed as

$$r_l(t) = \alpha_l e^{j\phi_l} s(t) + n_l(t),\ 0 \leq t \leq T_s, \tag{1}$$

where $s(t)$ is the transmitted symbol with energy E_s and $n_l(t)$ is the additive white Gaussian noise (AWGN) with two sided power spectral density $2N_0$. The RV ϕ_l represents the instantaneous phase of the signal received at the l^{th} branch and the RV α_l is the fading amplitude assumed to be Hoyt distributed whose PDF can be given by [2]

$$\begin{aligned} f(\alpha_l) &= \frac{2\alpha_l}{\Omega_l\sqrt{1-b_l^2}} \exp\left(-\frac{\alpha_l^2}{\Omega_l\left(1-b_l^2\right)}\right) \\ &\quad \times I_0\left(\frac{b_l^2\alpha_l^2}{\Omega_l(1-b_l^2)}\right), \alpha_l \geq 0, -1 \leq b_l \leq 1, \end{aligned} \tag{2}$$

where $\Omega_l = \mathrm{E}\left[\alpha_l^2\right]$, b_l is the fading severity parameter and $I_\nu(\cdot)$ is the νth-order modified Bessel function of the first kind.

Assuming spatial diversity fading signals are available, a predetection EGC receiver with the structure as shown in

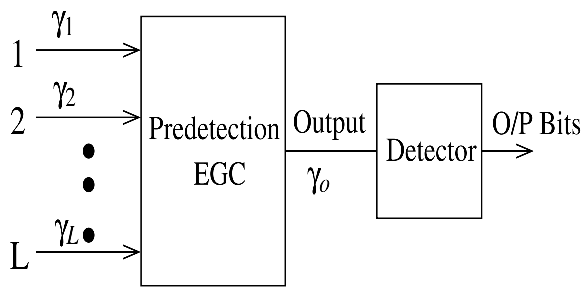

Fig. 1. Predetection EGC receiver

Fig. 1 has been used for receiving the signals. The receiver consists of an L-branch predetection EGC combiner followed by a detector. The L-branch predetection EGC combiner cophases the received signals and produces at its output the algebraic sum of these cophased signals. The detector following the combiner is suitable for the detection of the signal, corresponding to the modulation scheme employed at the transmitter.

The received instantaneous SNR at the l^{th} input branch of the EGC combiner can be given by $\gamma_l = \frac{E_s}{N_0}\alpha_l^2$, whose average value is $\bar{\gamma}_l = \frac{E_s}{N_0}\mathrm{E}\left[\alpha_l^2\right] = \frac{E_s}{N_0}\Omega_l$. Assuming ideal cophasing of L signals in the EGC combiner, the instantaneous output SNR of the predetection EGC receiver can be given by [2]

$$\gamma_o = (E_s/LN_0)\left(\alpha_1+\alpha_2+\ldots+\alpha_L\right)^2 \tag{3}$$

whose average value is $\bar{\gamma}_0 = (E_s/LN_0)\mathrm{E}[\alpha^2]$, where $\alpha = \alpha_1 + \alpha_2 + \ldots + \alpha_L$. An useful expression for the PDF of α i.e., the sum of arbitrary number of independent Hoyt distributed random variables has been presented in [7] using moment based estimators which can be given as

$$p_\alpha(\alpha) = \frac{4\sqrt{\pi}}{\Gamma(\mu)}\left(\frac{\mu}{\Omega}\right)^{\mu+\frac{1}{2}}\frac{\left(h\alpha^2\right)^\mu}{H^{\mu-\frac{1}{2}}}\exp\left(-\frac{2\mu h\alpha^2}{\Omega}\right) \times I_{\mu-\frac{1}{2}}\left(\frac{2\mu H\alpha^2}{\Omega}\right), \tag{4}$$

where $\Omega = \mathrm{E}\left[\alpha^2\right]$, $h \triangleq \left(2+\eta^{-1}+\eta\right)/4$ and $H \triangleq \left(\eta^{-1}-\eta\right)/4$. The parameters Ω, η and μ in (4) are required to be estimated for which the procedure is given in the Appendix. From (3) and using the relation $\Omega = \mathrm{E}\left[\alpha^2\right]$ the average output SNR can be obtained as $\bar{\gamma}_o = \frac{E_s}{LN_0}\Omega$.

An expression for the PDF of γ_o i.e., $p_{\gamma_o}(\gamma_o)$ can be obtained from (4), recognizing the relation between α and γ_0 from (3) (i.e., $\gamma_o = \frac{E_s}{LN_0}\alpha^2$) and using standard formula for the transformation of RVs. The authors in a recent publication have presented this PDF which can be given as [10]

$$p_{\gamma_o}(\gamma_o) = \frac{2\sqrt{\pi}h^\mu}{\Gamma(\mu)}\left(\frac{\mu}{\bar{\gamma}_o}\right)^{\mu+\frac{1}{2}}\left(\frac{\gamma_o}{H}\right)^{\mu-\frac{1}{2}} e^{\left(-\frac{2\mu h}{\bar{\gamma}_o}\gamma_o\right)} \times I_{\mu-\frac{1}{2}}\left(\frac{2\mu H}{\bar{\gamma}_o}\gamma_o\right). \tag{5}$$

Using (5) it is now convenient to analyze different performance measures of a predetection EGC receiver in independent Hoyt fading channels using the PDF-based approach.

III. Performance Analysis

A. Outage Probability

The outage probability P_{out} is a standard performance criterion characteristic of diversity communication systems operating over fading channels [1]. It is defined as the probability that γ_o falls below a specified threshold value γ_t. Mathematically,

$$P_{out} = \int_0^{\gamma_t} p_{\gamma_o}(\gamma_o)\,d\gamma_o. \tag{6}$$

For the predetection EGC receiver in independent Hoyt fading channels, P_{out} can be obtained by substituting (5) into (6). The integral in (6) can be solved by applying the identity [11, (3.381.1)]]. After simplification the expression for P_{out} can be given by

$$P_{out} = \frac{2^{1-2\mu}\sqrt{\pi}}{h^\mu\Gamma(\mu)}\sum_{k=0}^{\infty}\frac{\left(\frac{H}{2h}\right)^{2k}\gamma_f\left(2\mu+2k, \frac{2\mu h}{\bar{\gamma}_o}\gamma_t\right)}{k!\,\Gamma\left(\mu+k+\frac{1}{2}\right)}, \tag{7}$$

where $\gamma_f(\cdot,\cdot)$ is the incomplete gamma function [11].

B. Amount of Fading

The AF is the measure of the severity of the fading channel often appropriate in the more general context of describing the behavior of diversity systems with arbitrary, combining techniques and channel statistics [1]. It is defined as the ratio of the variance to the mean square value of the output instantaneous SNR γ_o. For predetection EGC receiver an expression for AF can be given by using γ_o from (3) as

$$AF = \frac{\mathrm{var}(\gamma_o)}{\bar{\gamma}_o^2} = \frac{E\left[\gamma_o^2\right]}{\bar{\gamma}_o^2} - 1 = \frac{E\left[\alpha^4\right]}{\Omega^2} - 1. \tag{8}$$

Thus, AF can be obtained by evaluating $\mathrm{E}\left[\alpha^4\right]$ from (19) for $k=4$ and then putting it in (8). Alternatively, it can also be evaluated by obtaining $\mathrm{E}\left[\alpha^4\right]$ directly from (4). The integration involved can be solved using the identity [11, (3.381.4)]. The final expression after simplification can be given as

$$AF = \frac{\mu+\frac{1}{2}}{\mu h^{\mu+2}}\,{}_3F_1\left(\mu+1, \mu+\frac{3}{2}, 1; \mu+\frac{1}{2}; \left[\frac{H}{h}\right)^2\right] - 1, \tag{9}$$

where ${}_3F_1(\cdot,\cdot,\cdot;\cdot;\cdot)$ is the hypergeometric function. The above expression converges fast since the magnitude of its argument $\frac{H}{h} < 1$.

C. Average Symbol Error Rate

For a given modulation scheme, the ASER of any receiver can be obtained by averaging the conditional SER $P(\varepsilon|\gamma)$ over the PDF of the receiver output SNR $p_\gamma(\gamma)$. It can be given by [2]

$$P_e = \int_0^{\infty} P(\varepsilon|\gamma)\,p_\gamma(\gamma)\,d\gamma. \tag{10}$$

TABLE I
PARAMETERS OF SEVERAL M-ARY MODULATION SCHEMES.
$f(\theta) = 1 - \cos(\pi/M)\cos\theta$ [2]

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Modulation	u_{max}	$a_u(\theta)$	$\beta(\theta)$	η_u
MPSK	1	$\frac{1}{\pi}$	$\frac{\sin^2(\pi/M)}{\sin^2\theta}$	$\pi - \frac{\pi}{M}$
MDPSK	1	$\frac{\sin(\pi/M)}{\pi f(\theta)}$	$f(\theta)$	$\pi/2$
MQAM	2	$\frac{-4}{\pi}\left(\frac{1}{\sqrt{M}} - 1\right)^u$	$\frac{1.5}{(M-1)\sin^2\theta}$	$\pi/(2u)$
MPAM	1	$\frac{2}{\pi}(1 - \frac{1}{M})$	$\frac{3}{(M^2-1)\sin^2\theta}$	$\pi/2$
DEBPSK	2	$\frac{2}{\pi}(-1)^{u-1}$	$\csc^2\theta$	$\pi/(2u)$

For an M-ary modulation scheme, $P(\varepsilon|\gamma)$ can be expressed in a unified manner as [2]

$$P(\varepsilon|\gamma) = \sum_{u=1}^{u_{max}} \int_0^{\eta_u} a_u(\theta) e^{-\gamma\beta(\theta)} d\theta, \tag{11}$$

where $a_u(\theta)$, $\beta(\theta)$, η_u and u_{max} are parameters of the modulation scheme. For a number of M-ary modulation schemes these parameter values have been listed in Table I.

A general expression for the ASER can be obtained by substituting (5) and (11) into (10) and solving the integral w.r.t γ_o. The indefinite integral involved can be analytically solved using the identity [11, (3.381.4)]. The final expression can be given by

$$P_e = \left(\frac{2\mu\sqrt{h}}{\bar{\gamma}_o}\right)^{2\mu} \sum_{k=0}^{\infty} \left(\frac{2\mu H}{\bar{\gamma}_o}\right)^{2k} \frac{(\mu)_k}{k!} \times \sum_{u=1}^{u_{max}} \int_0^{\eta_u} \frac{a_u(\theta)}{\left(\frac{2\mu h}{\bar{\gamma}_o} + \beta(\theta)\right)^{2x_k}} d\theta, \tag{12}$$

where $x_k \stackrel{\triangle}{=} \mu + k$ and $(\mu)_k$ is the Pochhammer's symbol [2].

The above expression (12) for the ASER of a predetection EGC receiver in Hoyt fading channels is useful for the following two major reasons:

1) It can be used for any digital modulation scheme for which the parameters $a_u(\theta)$, $\beta(\theta)$, η_u and u_{max} are known.
2) It is applicable for L-independent fading branches with arbitrary fading parameters $b_l, l = 1, 2 \ldots, L$.

The above expression contains a single integral with finite limits. Using the available software packages such as MATLAB and MATHEMATICA etc. this evaluation can be performed easily for a required degree of accuracy. It is also interesting to note that for some particular cases, discussed below, the above single definite integral can be analytically solved resulting in simple algebraic expressions.

Below we present some particular cases of the modulation schemes for which the above general expression (12) can be simplified further.

1) M-ary Phase Shift Keying Modulation: Substituting the parameters for MPSK modulation from Table I into (12), the ASER expression can be expressed as

$$P_{e,MPSK} = \frac{1}{\pi}\left(\frac{2\mu\sqrt{h}}{\bar{\gamma}_o}\right)^{2\mu} \sum_{k=0}^{\infty} \left(\frac{2\mu H}{\bar{\gamma}_o}\right)^{2k} \frac{(\mu)_k}{k!} \times \int_0^{\pi(1-\frac{1}{M})} \frac{d\theta}{\left[\frac{2\mu h}{\bar{\gamma}_o} + \left(\frac{\sin\frac{\pi}{M}}{\sin\theta}\right)^2\right]^{2x_k}}. \tag{13}$$

For the case of $M = 2$, i.e. for BPSK modulation, (13) can be solved using the identities [11, (3.211), (8.384.1)] which after further simplification can be given by

$$P_{e,BPSK} = \frac{1}{2\Gamma(\mu)}\left(\frac{\mu\sqrt{h}}{\bar{\gamma}_o}\right)^{2\mu} \sum_{k=0}^{\infty} \frac{\Gamma\left(2x_k + \frac{1}{2}\right)}{k! x_k \Gamma\left(x_k + \frac{1}{2}\right)} \times {}_2F_1\left(-2x_k, 2x_k + \frac{1}{2}; 2x_k + 1; \frac{-2\mu h}{\bar{\gamma}_o}\right), \tag{14}$$

where ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gaussian hypergeometric function [11].

2) M-ary Differential Phase Shift Keying Modulation: Substituting the parameters for MDPSK modulation from Table I into (12), the corresponding ASER expression can be given as

$$P_{e,MDPSK} = \left(\frac{2\mu\sqrt{h}}{\bar{\gamma}_o}\right)^{2\mu} \sum_{k=0}^{\infty} \frac{(\mu)_k}{k!} \int_0^{\pi/2} \frac{d\theta}{f(\theta)\left[\frac{2\mu h}{\bar{\gamma}_o} + f(\theta)\right]^{2x_k}}, \tag{15}$$

where $f(\theta)$ is defined in Table I.

For the case of $M = 2$, i.e. for binary DPSK modulation, (15) can be solved using the identities [11, (3.211),(8.384.1)] and the resulting simplified expression can be given by

$$P_{e,DPSK} = \left(\frac{2\mu\sqrt{h}}{\bar{\gamma}_o - 2\mu h}\right)^{2\mu} \sum_{k=0}^{\infty} \left(\frac{2\mu H}{\bar{\gamma}_o - 2\mu h}\right)^{2k} \frac{(\mu)_k}{k!} \tag{16}$$

IV. NUMERICAL EVALUATION

Analytical expressions for P_{out} (7), AF (8) and ASER (13)-(16) have been numerically evaluated. For the purpose of simplification of evaluation, without loss of generality, we have assumed $\Omega_l|_{l=1}^{L} = 1$. This enables us to express $\bar{\gamma}_l = E_s/N_0$ which is convenient for all evaluations. The value of fading parameter has been assumed to be identical for all branches i.e. $b_1 = b_2 = \ldots = b_L = b$. The outage probability P_{out} has been evaluated as a function of the ratio $\bar{\gamma}_1/\gamma_t$ by expressing $\bar{\gamma}_o/\gamma_t = (\bar{\gamma}_1/\gamma_t)(\Omega/L)$ in (7). The value of Ω for any L can be obtained by evaluating (19) for $k = 2$. For *unequal* branch SNR case, an exponentially decaying power delay profile given by $\Omega_l = \Omega_1 e^{-\delta(l-1)}, 0 \leq \delta \leq 1$, has been assumed [1]. Evaluation of each expression requires the values of H and h which can be obtained by first obtaining the values of η and μ from (17)-(20) in the Appendix and then substituting them into (4). In the evaluation of the expressions involving infinite series, 20

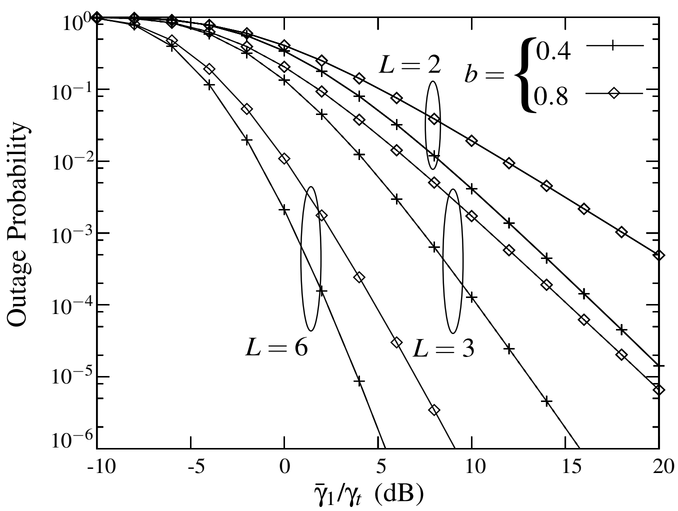

Fig. 2. Outage probability P_{out} vs. $\bar{\gamma}_1/\gamma_t$ for different L and b.

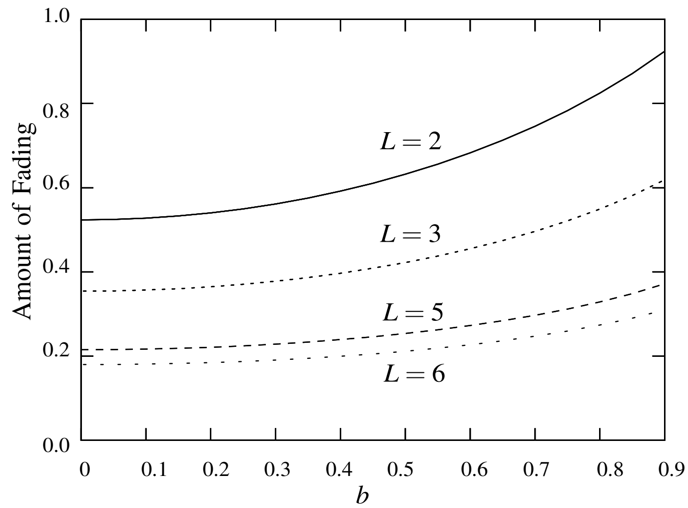

Fig. 3. Amount of fading vs. b for $L = 2,3,5$ and 6.

terms have been found to be sufficient for an accuracy at least up to 7th place of decimal digit.

V. Results and Discussion

In Fig. 2 P_{out} versus $\bar{\gamma}_1/\gamma_t$ has been plotted for different values of L and b. It can be observed from this figure that P_{out} decreases from a maximum value of unity to very small values with increase in the ratio $\bar{\gamma}_1/\gamma_t$. This implies that the outage, for a fixed $\bar{\gamma}_1$, varies directly with γ_t, which is intuitively satisfying. It can also be observed that for a fixed γ_t, P_{out} reduces with increase in L. It is due to the reason that including more number of branches improves $\bar{\gamma}_o$ resulting in less outage. Further, it can be noted that for a given L, P_{out} varies directly with b, as expected. The outage probability results obtained here have been compared with the published results in [5, Fig. 5, $L = 2,3$] and found to be matching closely. AF versus channel parameter b has been plotted for different values of L in Fig. 3. From the curves shown, it can be inferred that the severity of fading increases with increase in the fading parameter b and decreases with increase in L.

ASER versus SNR E_s/N_0 per branch has been plotted for MPSK and MDPSK modulations in Figs. 4 and 5, respectively. Curves for ASER have been shown for $L = 2,3$ and 6, each one for $M = 2,4$ and 8. The value of b has been taken to be 0.5 in these plots. The common observation is that the ASER decreases with increase in E_s/N_0 and L whereas it increases with increase in M, which is as expected. It is important to observe the low SNR region of these plots where the curves are either crossing each other or overlapping. This indicates that in this region of SNR the ASER of the receiver is almost independent of M and L. This gives an option to choose a less complex modulation scheme and/or less number of branches when receivers are likely to operate in low SNR environments. The plotted results have been compared with the matching cases in [5, Figs. 4(a) and 4(b)] and found to be matching closely. This observation validates the accuracy

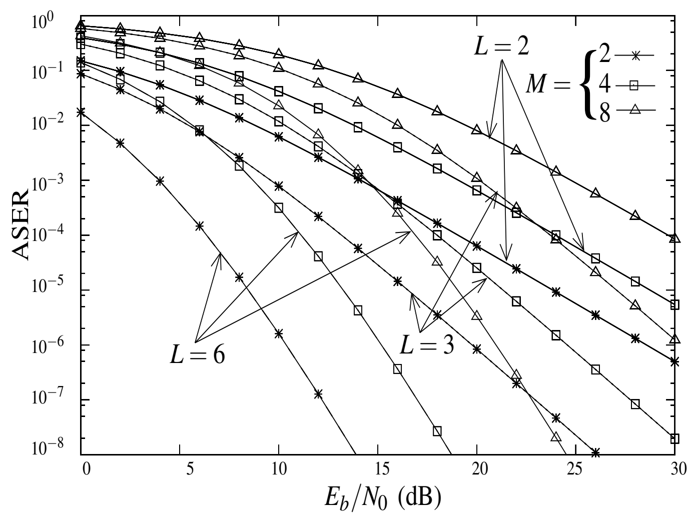

Fig. 4. ASER vs. E_s/N_0 for MPSK modulation for different L and M.

of our derivations. ASER versus E_s/N_0 for unequal branch SNRs and arbitrary fading parameters b_l has been shown in Fig. 6. For the purpose of illustration, curves have been shown for $L = 3$ and 5 each one for $\delta = 0, 0.5$ and 1 for 4PSK modulation. For each L, we have arbitrarily taken $b_1 = 0.3$ and $b_l = b_1 + 0.1, 2 \le l \le L$. The observations from these plots can be explained in the manner similar to that presented for equal branch SNR case.

VI. Conclusion

In this paper, we have analyzed the performance of a L-branch predetection EGC diversity receiver in independent Hoyt fading channels, with non-identical and arbitrary fading parameters, applying the PDF based approach. Using an approximate but highly accurate expression for the PDF of the sum of independent Hoyt RVs, expressions for the outage probability, amount of fading and ASER have been obtained. The ASER expression is in the form of an infinite series

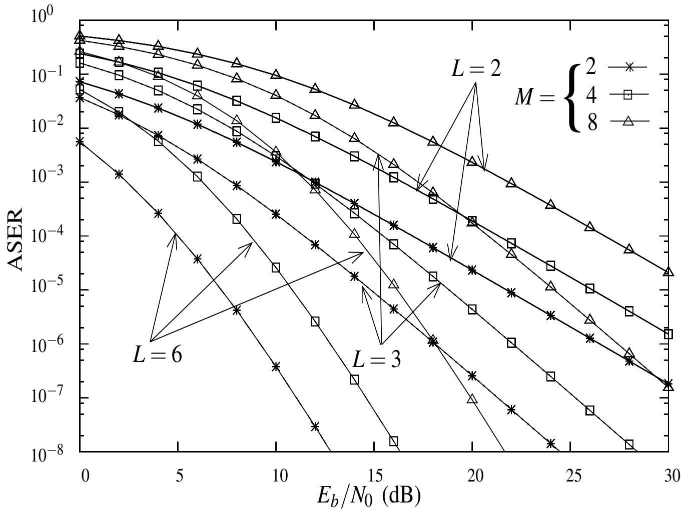

Fig. 5. ASER vs. E_s/N_0 for MDPSK modulation for different L and M.

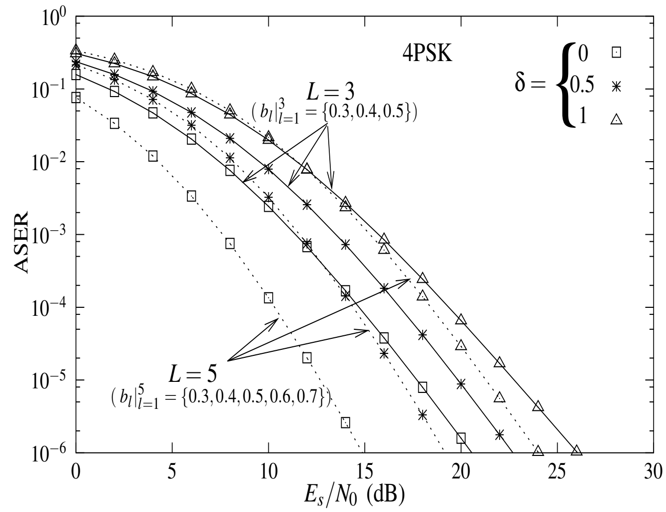

Fig. 6. ASER vs. E_s/N_0 for unequal branch SNRs for 4PSK modulation.

with a single integral having finite limits and is applicable for a number of coherent and noncoherent modulation schemes. For the purpose of illustration, simplified expressions for the MPSK and MDPSK modulations have also been given. For binary modulation cases, these finite integral expressions have been solved to the expressions containing elementary and special mathematical functions. Numerically evaluated results have been plotted and compared with the particular cases of the published results to check the correctness of the obtained analytical expressions.

Appendix
Estimators for Hoyt Random Variables

The expressions to obtain parameters Ω, η and μ are reproduced below from [7]:

$$\eta_{1,2} = \frac{\sqrt{2c}-\sqrt{3-2c\pm\sqrt{9-8c}}}{\sqrt{2c}+\sqrt{3-2c\pm\sqrt{9-8c}}}, \quad (17)$$

$$\mu_{1,2} = \frac{\Omega^2}{\mathrm{E}[\alpha^4]-\Omega^2}\frac{1+\eta_{1,2}^2}{(1+\eta_{1,2})^2}, \quad (18)$$

where $\Omega=\mathrm{E}\left[\alpha^2\right]$ and $c \triangleq \frac{\frac{\mathrm{E}[\alpha^6]}{\Omega^3}-\frac{3\mathrm{E}[\alpha^4]}{\Omega^2}+2}{2\left(\frac{\mathrm{E}[\alpha^4]}{\Omega^2}-1\right)^2}$. From (17) and (18) two pairs of η and μ are possible i.e. $(\eta_i,\mu_i), i=1,2$. The appropriate pair is the one for which the deviation $|\mathrm{E}[\alpha]-\mathrm{E}[\alpha]_i|, i=1,2$ is the smallest.

The formula to obtain the moments of α is given as below:

$$\mathrm{E}\left[\alpha^k\right] = \sum_{k_1=0}^{k}\sum_{k_2=0}^{k_1}\cdots\sum_{k_{L-1}=0}^{k_{L-2}}\begin{pmatrix}k\\k_1\end{pmatrix}\begin{pmatrix}k_1\\k_2\end{pmatrix}\cdots\begin{pmatrix}k_{L-2}\\k_{L-1}\end{pmatrix} \times\mathrm{E}\left[\alpha_1^{k-k_1}\right]\mathrm{E}\left[\alpha_2^{k_1-k_2}\right]\ldots\mathrm{E}\left[\alpha_L^{k_{L-1}}\right] \quad (19)$$

The k^{th} moment of Hoyt summand α_l is given by

$$\mathrm{E}\left[\alpha_l^k\right] = \left(1-b_l^2\right)^{\frac{1+k}{2}}\Gamma\left(1+\frac{k}{2}\right)\Omega_l^{k/2}\,{}_2F_1\left(1+\frac{k}{4},\frac{1}{2}+\frac{k}{4};1;b_l^2\right). \quad (20)$$

References

[1] M. K. Simon, and M. S. Alouini, *Digital Communication over Fading Channels,* 2nd Ed., John Wiley & Sons, Inc., 2005.

[2] A. Annamalai, C. Tellambura, and Vijay K. Bhargava, "Equal Gain Diversity Receiver Performance in Wireless Channels," *IEEE Trans. on Commun.,* vol. 48, No. 10, pp.1732-1745, Oct. 2000.

[3] A. A. Abu-Dayya and N. C. Beaulieu, "Microdiversity on Rician fading channels," *IEEE Trans. on Commun.,* vol. 42, pp. 2258-2267, Jun. 1994.

[4] Q. T. Zhang, "Probability of Error for Equal-Gain Combiners Over Rayleigh Channels: Some Closed-Form Solutions," *IEEE Trans. on Commun.*, vol. 45, No. 3, pp. 270-273, Mar. 1997.

[5] D. A. Zogas, G. K. Karagiannidis and S. A. Kotsopoulos, "Equal gain combining over Nakagami-n (Rice) and Nakagami-q (Hoyt) generalized fading channels," *IEEE Trans. on Wireless Commun.,* vol. 4, no. 2, pp. 374- 379, Mar. 2005.

[6] Cyril-Daniel Iskander and P. T. Mathiopoulos, "Exact performance analysis of dual-branch equal-gain combining in Nakagami-m, Rician and Hoyt fading," *IEEE Trans. Veh. Technol,* vol. 57, no. 2, pp. 921-931, Mar. 2008.

[7] Jose C. Silveira Santos Filho and Michel Dacoud Yacoub, "Highly accurate $\eta-\mu$ approximation to the sum of M independent nonidentical Hoyt variates," *IEEE Antennas and Wireless Propagation Lett.,* vol. 4, pp. 436-438, 2005.

[8] M D Yacoub et al., "The Symmetrical $\eta-\kappa$ Distribution: A General Fading Distribution," *IEEE Trans. on Broad.,* vol. 51, no. 4, Dec. 2005.

[9] M. D. Yacoub, "The $\kappa-\mu$ and $\eta-\mu$ distribution," *IEEE Antenna and Propagation Mag.,* vol. 49, no. 1, pp. 68-81, Feb. 2007.

[10] A. Baid, H. Fadnavis and P. R. Sahu, "Performance of a predetection EGC receiver in Hoyt fading channels for arbitrary number of branches," *IEEE Commun. Lett.,* vol. 12, no. 9, pp. 627-629, Sept. 2008.

[11] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products,* 5th ed., San Diego, CA: Academic, 1994.