Dual-Branch Diversity Receivers over Correlated Rician Fading Channels

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***Abstract*— In this paper the performance of dual-branch diversity receivers operating over *correlated* Rician fading channels is analyzed and novel performance evaluation results are presented. By representing the bivariate Rician probability density function of the signal-to-noise ratio (SNR) as a rapidly converging infinite sum, useful analytical expressions for the performance of dual-branch selection combining and maximal ratio combining receivers are derived. Capitalizing on these infinite series representations, novel analytical formulae for the average bit-error and outage probability are obtained. The proposed analysis is used to obtain various novel performance evaluation results having as parameters of interest fading severity, average SNR and Rician correlation coefficient. The series convergence rate is also studied verifying the fast convergence of the analytical expressions. The accuracy of most of the theoretical results have been verified by means of computer simulation.**

I. Introduction

One of the simplest and yet most efficient techniques to overcome the destructive effects of fading in wireless communication systems is diversity. For all diversity techniques the receiver has to process the obtained diversity signals in a way that maximizes the system's power efficiency. There are several diversity reception methods employed in digital communication receivers including equal-gain combining (EGC), maximal-ratio combining (MRC), selection combining (SC) [1]. Clearly though, the performance of these diversity techniques depends on the characteristics of the multipath fading envelopes.

In the past, several statistical distributions have been proposed for channel modeling, including Rayleigh, Nakagami-m, Rician and more recently the Weibull distribution [1]–[4]. Specifically, the Rician distribution is often used to model propagation paths consisting of one strong direct line-of-sight component and many multipath components. It is a very useful and widely used channel model as it spans in range from Rayleigh fading to no fading cases and is typically observed in microcellular, urban land mobile communications and mobile satellite radio links [5]–[7]. However, despite the obvious practical importance of studying the performance of dual-diversity receivers operating over *correlated* Rician fading channels, this research topic has not been adequately addressed in open technical literature. Reasons for this include the complicated form of the bivariate Rician probability density function (PDF) and the absence of alternative expressions for the multivariate distribution.

Representative past work concerning the performance of dual-diversity receivers operating over correlated fading channels can be found in [3], [8]–[11]. Malik *et al.*, in [8], have presented an efficient approach in analyzing the performance of coherent detection for binary signals with dual-diversity in correlative Rayleigh fading. Karagiannidis *et al.*, in [9], have derived a convergent infinite sum expression for the characteristic function of two correlated Nakagami-m variables. In [3], considering the dual-diversity receivers operating in correlated Weibull fading channels, analytical expressions for several performance criteria have been derived in closed-forms. For the Rician fading channel in [10], a study for dual-branch EGC in slow, correlated, Rician time selective fading has been presented for the special case of non-coherent detection of orthogonal binary frequency-shift keying (BFSK). More recently, in [11], the cumulative distribution functions (CDF) of the SC output signal-to-noise (SNR) in equally correlated Rayleigh, Rician and Nakagami-m fading channels, have been derived. However, for the Rician fading channel only the outage probability of SC was derived in [11]. Thus, to the best of our knowledge, a detailed performance analysis for the *correlated* Rician fading channel of SC and MRC receivers has not yet been published in the open technical literature, and thus this is the topic of the current paper.

This paper is organized as follows. After this introduction, in Section II, novel infinity series representation of the joint Rician PDF, CDF and moments-generating function (MGF) are derived. In Section III, important performance criteria of dual-branch SC and MRC receivers are studied, while in Section IV several numerical evaluating results are presented.

II. System Model and Infinite Series Analysis

Let us consider a dual-branch diversity receiver operating over correlated Rician fading channel. As other papers in the past (e.g., [8], [12]) it is assumed that the additive white Gaussian noise (AWGN), between the two diversity branches, is uncorrelated, fading is slowly varying, and hence, perfect channel estimation can be obtained [1]. The joint PDF of the correlated Rician instantaneous SNR per symbol, γ_1 and γ_2, can be expressed as [5]

$$f_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2)=\frac{(1+K)^2\exp\left[-\frac{2K}{1+\rho}-\frac{(1+K)(\gamma_1+\gamma_2)}{2(1-\rho^2)\overline{\gamma}}\right]}{2\pi\overline{\gamma}^2(1-\rho^2)}\times\int_0^{2\pi}\exp\left[\frac{2\rho(1+K)\sqrt{\gamma_1\gamma_2}\cos\theta}{(1-\rho^2)\overline{\gamma}}\right]\times I_0\left[\sqrt{\frac{4K(1+K)\left(\gamma_1+\gamma_2+2\sqrt{\gamma_1\gamma_2}\cos\theta\right)}{\overline{\gamma}(1+\rho)^2}}\right]d\theta \tag{1}$$

where K is the Rician factor, defined as the ratio of the specular signal power to the scattered power, $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind [13, Section 8.40], $\overline{\gamma}$ is the average SNR per symbol in both input branches and ρ is Rician correlation coefficient between R_1 and R_2, presented in the Appendix.

It can be easily observed that the PDF in the form given by (1) is very difficult, if not impossible, to be used for the performance analysis of dual-branch diversity receivers. An alternative approach would be to obtain a new infinite sum representation for this PDF. Hence, using an infinite series representation of $I_0(\cdot)$ [13, eq. (8.445)], the multinomial identity to the term $\left(\zeta_1+\zeta_2+2\sqrt{\zeta_1\zeta_2}\cos\theta\right)^i$, the transformation $x=\cos\theta$, substituting the hypergeometric function ${}_1F_2(\cdot;\cdot,\cdot;\cdot)$ with its infinite series representation given by [13, eq. (9.14/1)] and after some straightforward mathematical manipulations, (1) becomes

$$f_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}t^{t_3}\gamma_1^{t_1}\gamma_2^{t_2}\left(1-\rho^2\right)^{i+1}\left(\mathcal{B}-\mathcal{C}\sqrt{\gamma_1\gamma_2}\right)}{2^{-v_3-2h+1}\exp\left[t\left(\gamma_1+\gamma_2\right)\right]} \tag{2}$$

where

$$\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}=\sum_{i=0}^{\infty}\sum_{v_1=0}^{i}\sum_{v_2=0}^{i}\sum_{\substack{v_3=0\\v_1+v_2+v_3=i}}^{i}\sum_{h=0}^{\infty},$$

$$\mathcal{A}=\frac{\rho^{2h}\exp\left(-2K/(1+\rho)\right)}{\sqrt{\pi}v_1!\,v_2!\,v_3!\,i!}\left(\frac{K}{(1+\rho)^2}\right)^i,$$

$$\mathcal{B}=\left[1+(-1)^{v_3}\right]\frac{\Gamma\left(h+(1+v_3)/2\right)}{(2h)!\Gamma\left(1+h+v_3/2\right)},$$

$$\mathcal{C}=\left[-1+(-1)^{v_3}\right]\frac{2\rho(1+K)\Gamma\left(h+1+v_3/2\right)}{(1-\rho^2)\overline{\gamma}(1+2h)!\Gamma\left(h+(3+v_3)/2\right)}$$

$t=(1+K)/\left[\left(1-\rho^2\right)\overline{\gamma}\right]$, $t_1=v_1+v_3/2+h$, $t_2=v_2+v_3/2+h$ and $t_3=2+i+2h$.

Using (2), [13, eq. (3.381/4)] and the definition of the joint MGF of γ_1 and γ_2 [14, eq. (7.23)], an analytical but cumbersome expression for this joint MGF, involving series of sums, can be obtained as

$$\mathcal{M}_{\gamma_1,\gamma_2}(s_1,s_2)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}(1+K)^{t_3}}{2^{-v_3-2h+1}\overline{\gamma}^{t_3}\left(1-\rho^2\right)^{1+2h}}\times\left[\frac{\mathcal{B}}{(s_1+t)^{1+t_1}(s_2+t)^{1+t_2}}-\mathcal{C}\frac{\Gamma\left(\frac{3}{2}+t_1\right)\Gamma\left(\frac{3}{2}+t_2\right)}{\sqrt{(s_1+t)(s_2+t)}}\right]. \tag{3}$$

Using (2) and [14, eq.(7.18)] the joint moments of γ_1 and γ_2 can be derived as

$$\mu_{\gamma_1,\gamma_2}(k,n)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}(1+K)^{t_3}\,t^{-(3+n+k+t_1+t_2)}}{2^{-v_3-2h+1}\,\overline{\gamma}^{t_3}\left(1-\rho^2\right)^{1+2h}}\left[(n+t_1)!\times\mathcal{B}\,(k+t_2)!-\mathcal{C}\,\Gamma\left(\frac{3}{2}+n+t_1\right)\Gamma\left(\frac{3}{2}+k+t_2\right)\right]. \tag{4}$$

By substituting (2) in the joint CDF of γ_1 and γ_2, [14, eq. (6.6)], interchanging the order of summations and integrations and after some straightforward mathematical simplifications, the joint CDF of γ_1 and γ_2 can be expressed in sums as

$$F_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}\left(1-\rho^2\right)^{i+1}}{2^{-v_3-2h+1}}\left[\mathcal{B},\gamma\left(t_1+1,t\,\gamma_1\right)\times\gamma\left(t_2+1,t\,\gamma_2\right)-\frac{\mathcal{C}}{t\,\gamma\left(t_1+3/2,t\,\gamma_1\right)\gamma\left(t_2+3/2,t\,\gamma_2\right)}\right] \tag{5}$$

where $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function [13, eq. (8.350/1)].

III. Performance Analysis

A. SC Receivers

1) Outage probability: By defining the instantaneous SNR at the SC receiver output as $\gamma_{sc}\overset{\triangle}{=}\max(\gamma_1,\gamma_2)$, the CDF of γ_{sc} can be expressed as $F_{\gamma_{sc}}(\gamma)=F_{\gamma_1,\gamma_2}(\gamma,\gamma)$. The outage probability, $P_{out}(\gamma_{th})$, is defined as the probability that γ_{sc} falls below a given threshold, γ_{th}. Hence, $P_{out}(\gamma_{th})$ can be simply obtained as $P_{out}(\gamma_{th})=F_{\gamma_{sc}}(\gamma_{th})$.

2) Average output SNR and A_F: By differentiating $F_{\gamma_{sc}}(\gamma)$ with respect to γ, the PDF of γ_{sc} can be derived as

$$f_{\gamma_{sc}}(\gamma)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}\left(1-\rho^2\right)^i(1+K)\,t^{t_2}}{2^{-v_3-2h+1}\,\overline{\gamma}\,\exp(t\,\gamma)}\times\left\{\mathcal{B}\left[\gamma^{t_2}\,\gamma\left(t_1+1,t\,\gamma\right)+\frac{\gamma^{t_1}\,\gamma\left(t_2+1,t\,\gamma\right)}{t^{v_2-v_1}}\right]-\frac{\mathcal{C}\,\gamma^{t_2+1/2}}{\sqrt{t}}\left[\gamma\left(t_1+3/2,t\,\gamma\right)+\frac{\gamma\left(t_2+3/2,t\,\gamma\right)}{(t\,\gamma)^{v_2-v_1}}\right]\right\}. \tag{6}$$

Using (6) in the definition of the nth moment of a variable, [14, eq. (5.38)], and interchanging the order of summation and integration, some integrals of the form $I=$

$$\mathcal{M}_{\gamma_{sc}}(s)=\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}\left(1-\rho^2\right)^i(1+K)t^{t_3-1}}{2^{-v_3-2h+1}\,\overline{\gamma}(t-s)^{-t_3}}\left\{\mathcal{B}\left[\frac{{}_2F_1\left[t_1+1,t_3;t_1+2;-t/(t-s)\right]}{t_1+1}+\frac{{}_2F_1\left[t_2+1,t_3;t_2+2;-t/(t-s)\right]}{t_2+1}\right]\right.$$
$$\left.\times(t_3-1)!-\frac{\mathcal{C}\,(t_3)!}{(t-s)^{-1}}\left[\frac{{}_2F_1\left[t_1+3/2,t_3+1;t_1+5/2;-t/(t-s)\right]}{t_1+3/2}+\frac{{}_2F_1\left[t_2+3/2,t_3+1;t_2+5/2;-t/(t-s)\right]}{t_2+3/2}\right]\right\}\quad(10)$$

$\int_0^\infty y^a\exp(-\xi\,y)\,\gamma(u,\Xi\,y)\,dy$ need to be solved, where a, ξ, u and Ξ positive constants. By representing the lower incomplete Gamma function as $\gamma(u,\Xi\,y)=(\Xi\,y)^u\,{}_1F_1(u;u+1;-\Xi\,y)/u$, [15, eq. (6.5.12)], I can be solved using [13, eq. (7.621/4)] as

$$I=\frac{\Xi^u\,\Gamma\left(\alpha+u+1\right)}{\xi^{\alpha+u+1}\,u}\,{}_2F_1\left(u,\alpha+u+1;u+1;-\frac{\Xi}{\xi}\right)\quad(7)$$

where ${}_2F_1\left(\cdot,\cdot;\cdot;\cdot\right)$ is the Gauss hypergeometric function [13, eq. (9.100)]. Hence, using (7), the nth moment of γ_{sc} can be expressed in closed form as

$$\begin{aligned}\mu_{\gamma_{sc}}(n)=&\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}\left(1-\rho^2\right)^i(1+K)}{2^{-v_3-2h+1}\,\overline{\gamma}\,t^{(1+n)}}\left\{\mathcal{B}\Gamma\left(n+t_3\right)\right.\\&\times\left[\frac{{}_2F_1\left(t_1+1,t_3+n;t_1+2;-1\right)}{t_1+1}\right.\\&\left.+\frac{{}_2F_1\left(t_2+1,t_3+n;t_2+2;-1\right)}{t_2+1}\right]-\frac{\Gamma\left(t_3+1+n\right)}{t}\\&\times\left[\frac{{}_2F_1\left(t_1+3/2,t_3+n+1;t_1+5/2;-1\right)}{t_1+3/2}\right.\\&\left.\left.+\frac{{}_2F_1\left(t_2+3/2,t_3+n+1;t_2+5/2;-1\right)}{t_2+3/2}\right]\right\}.\end{aligned}\quad(8)$$

From the above equation, the average output SNR, $\overline{\gamma}_{sc}$, can be obtained by setting $n=1$. Furthermore, the AoF can be also easily obtained since it is given by

$$A_F\triangleq\frac{\mathrm{var}\left(\gamma_{sc}\right)}{\overline{\gamma}_{sc}^2}=\frac{\mu_{\gamma_{sc}}(2)}{\overline{\gamma}_{sc}^2}-1.\quad(9)$$

3) ABEP performance: Substituting (6) to [14, eq.(5.62)] results integrals of the form I. Thus, following a similar procedure as for deriving (8), the MGF of γ_{sc} can be obtained as in (10) (top of this page). By using this MGF expression of the combined output SNR, the ABEP can be readily evaluated for a variety of modulation schemes [1].

B. MRC Receivers

The MGF of γ_{mrc} can be obtained using (3) as

$$\mathcal{M}_{\gamma_{mrc}}(s)=\mathcal{M}_{\gamma_1,\gamma_2}(s,s).\quad(11)$$

1) ABEP performance: Using the (11) the ABEP can be calculated easily similarly to the ABEP analysis of dual-branch SC receivers.

2) Outage probability: The CDF of γ_{mrc} can be derived as

$$F_{\gamma_{mrc}}(\gamma)=\mathcal{L}^{-1}\left\{\frac{\mathcal{M}_{\gamma_{mrc}}(s)}{s};\gamma\right\}_{s=0}\quad(12)$$

where $\mathcal{L}^{-1}\left\{\cdot,\cdot\right\}$ denotes inverse Laplace transforming. After some straightforward mathematical manipulations, this CDF can be expressed as

$$\begin{aligned}F_{\gamma_{mrc}}(\gamma)=&\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}(1+K)^{t_3}t^{-(2+t_1+t_2)}}{2^{-v_3-2h+1}\,\overline{\gamma}^{t_3}\left(1-\rho^2\right)^{1+2h}}\\&\times\left\{\mathcal{B}t_1!\,t_2!\frac{\left[\Gamma\left(t_3\right)-\Gamma\left(t_3,\gamma\,t\right)\right]}{\Gamma\left(t_3\right)}-\frac{\mathcal{C}\,\Gamma\left(3/2+t_1\right)}{t\,\Gamma\left(1+t_3\right)}\right.\\&\left.\times\Gamma\left(3/2+t_2\right)\left[\Gamma\left(1+t_3\right)-\Gamma\left(1+t_3,\gamma t\right)\right]\right\}.\end{aligned}\quad(13)$$

Using (13), $P_{out}\left(\gamma_{th}\right)$ can be obtained as

$$P_{out}\left(\gamma_{th}\right)=F_{\gamma_{mrc}}\left(\gamma_{th}\right)\quad(14)$$

3) Average output SNR and AoF: By differentiating (13) with respect to γ, the PDF of γ_{mrc} can be obtained as

$$\begin{aligned}f_{\gamma_{mrc}}(\gamma)=&\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}(1+K)^{t_3}\,\gamma^{1+t_1+t_2}\exp(-\gamma\,t)}{2^{-v_3-2h+1}\overline{\gamma}^{t_3}\left(1-\rho^2\right)^{1+2h}}\\&\times\left[\mathcal{B}\,t_1!\,t_2!\,\Gamma\left(t_3\right)-\frac{\mathcal{C}\,\Gamma\left(3/2+t_1\right)\Gamma\left(3/2+t_2\right)\gamma}{\Gamma\left(1+t_3\right)}\right].\end{aligned}\quad(15)$$

Hence, using the above equation and with the aid of [14, eq.(7.18)], the nth order moment of γ_{mrc} can be expressed as

$$\begin{aligned}\mu_{\gamma_{mrc}}(n)=&\sum_{\substack{i,h=0\\v_1+v_2+v_3=i}}^{\infty}\frac{\mathcal{A}(1+K)^{t_3}}{2^{-v_3-2h+1+n}\overline{\gamma}^{t_3}\left(1-\rho^2\right)^{1+2h}}\\&\times\frac{t^{-(1+n+t_3)}}{\Gamma\left(t_3\right)\Gamma\left(1+t_3\right)}\left\{\mathcal{B}t_1!\,t_2!\,t\,\Gamma\left(1+t_3\right)\Gamma\left(n+t_3\right)\right.\\&\left.-\,\mathcal{C}\Gamma\left(3/2+t_1\right)\Gamma\left(3/2+t_2\right)\Gamma\left(t_3\right)\Gamma\left(1+n+t_3\right)\right\}.\end{aligned}\quad(16)$$

By setting $n=1$ in (16), the average output SNR, $\overline{\gamma}_{mrc}$, can be obtained, whereas the AoF can be also easily derived using (9) and the above equation.

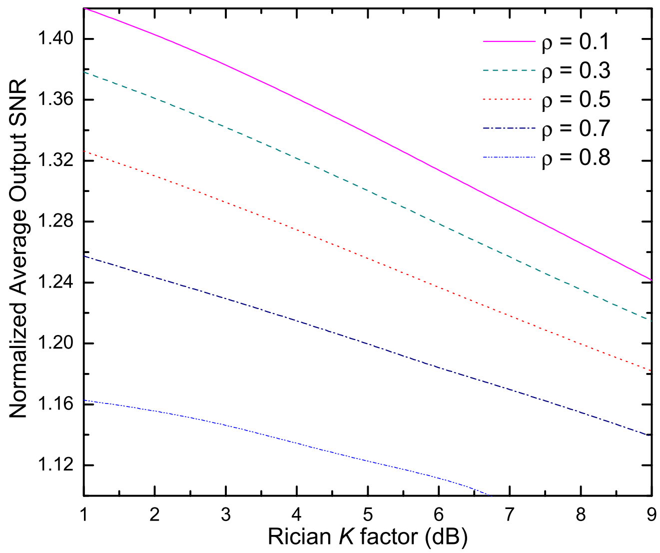

Fig. 1. SC performance: $\overline{\gamma}_{sc}/\overline{\gamma}$ versus K for different values of ρ.

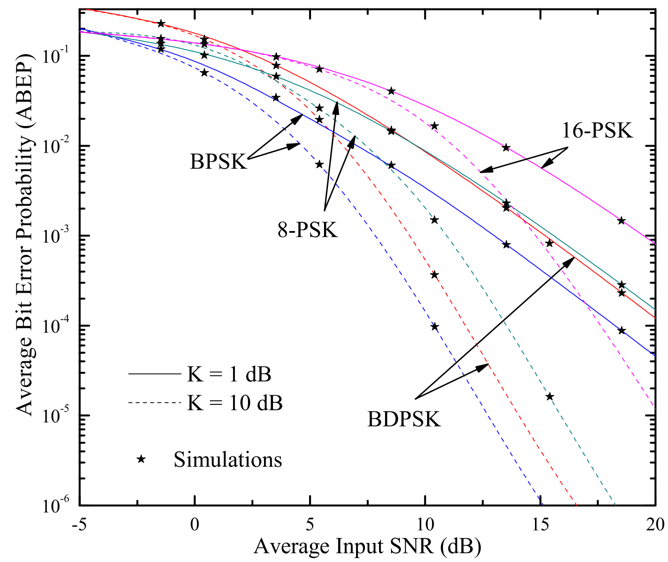

Fig. 2. SC performance with DPSK and M-PSK signals: ABEP versus $\overline{\gamma}$ for $K = 1$ and 10 dB.

IV. Numerical Results and Discussion

In this section, representative performance evaluation results for the SC and MRC receivers, such as the normalized average output SNR, ABEP and P_{out} for terrestrial and satellite communication systems are presented. These performance results were obtained using the infinite series expressions derived in the previous section. As compared to alternative solutions involving integrals, the series representations offer the following two distinct advantages: *i)* flexibility in the performance analysis and *ii)* significant reduction of the convergence rate.

Using (8), the $\overline{\gamma}_{sc}/\overline{\gamma}$ performance as a function of K and with ρ as a parameter, is presented in Fig. 1. As K and/or ρ decreases $\overline{\gamma}_{sc}/\overline{\gamma}$ increases. It is interesting to note that $\overline{\gamma}_{sc}/\overline{\gamma}$ degrades more rapidly as ρ increases.

In Fig. 2, the ABEP performance of dual-branch SC (see (10)) receiver is plotted for DBPSK and M-PSK[1], for $\rho = 0.5$ and several values of the Rician-K factor. As expected, the ABEP improves as the average SNR of the input branch, $\overline{\gamma}$, increases, while for a fixed value of $\overline{\gamma}$ it also improves as K increases. Similar behavior is also noted in Fig. 3 for the ABEP of 16-QAM signaling[1], which is also plotted as a function of $\overline{\gamma}$ for several values of K and ρ. Fig. 4, which was obtained by using the results of Section III-A, illustrates P_{out} versus $\overline{\gamma}/\gamma_{th}$ for several values of K and ρ. The outage performance deteriorates with an increase of the correlation between the two diversity paths, i.e., higher values of ρ. Moreover, as K increases P_{out} decreases, meaning that the outage performance improves. In order to verify the validity of the theoretically derived formulae equivalent computer simulated performance results are also included for all ABEP performance results presented in Figs. 2–3. The excellent agreement between simulated and analytical results confirms the correctness of the theoretical derivations.

[1]Where applicable, only Gray encoded signals are considered in this section.

TABLE I
Minimum Number of Terms (N_{min}) Required for Seven Significant Figure Accuracy of ABEP

	$K = 1$ dB		$K = 7$ dB	
$\overline{\gamma}$ (dB)	$\rho = 0.2$	$\rho = 0.7$	$\rho = 0.2$	$\rho = 0.7$
-5	13	28	26	44
0	11	18	24	39
5	9	9	18	23
10	5	4	11	13
15	3	3	7	7
20	2	2	4	4

Finally, the rate of convergence of the infinite series representation has also been investigated. The minimum number of terms, N_{min}, which guarantees seven significant figure accuracy (e.g. 10^{-7} or better) is presented for a typical case: ABEP of DBPSK signals versus $\overline{\gamma}$ (see (10)) in Table I, for different values of ρ and K assuming, without loss of generality that $i = h$. It is clear from these results that only a relatively small number of terms are necessary to achieve an excellent accuracy and the required number of terms is significantly smaller than the corresponding ones for the Nakagami-m case, [16], [17]. It is worthwhile to mention that very similar results with Table I were also obtained by using other modulation formats, such as M-QAM and M-PSK.

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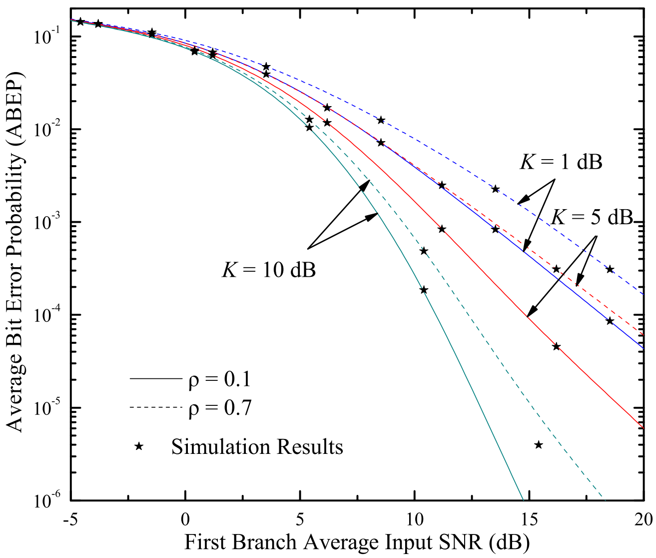

Fig. 3. MRC performance with M-QAM signals: ABEP versus $\overline{\gamma}$ for $K = 1$, 5 and 10 dB and $\rho = 0.1$ and 0.7.

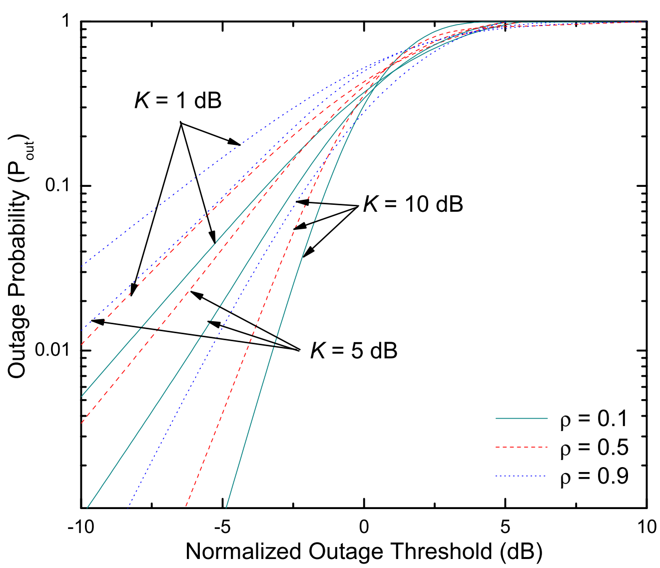

Fig. 4. SC performance: P_{out} versus $\overline{\gamma}/\gamma_{th}$ for several values of K and ρ.

Appendix
Rician Correlation Coefficient

The formula between the correlation coefficient of Rice, ρ, and Rayleigh ϱ, fading, can be derived by replacing in [14, eq.(7.8)] R_1 and R_2 with $K + R_1$ and $K + R_2$, respectively, where after straightforward mathematical manipulations yields

$$\rho = \frac{\pi}{4-\pi}\left[(1-\varrho)^2 {}_2F_1\left(\frac{3}{2}, \frac{3}{2}, 1; \varrho\right) - 1\right]. \qquad \text{(A-1)}$$

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