Performance of L-branch Diversity Combiners in Equally Correlated Rician Fading Channels

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***Abstract*— Despite the importance of the Rician fading model in describing microcellular, picocellular and mobile satellite channels, few theoretical results are known about the performance of selection combining (SC) and equal gain combining (EGC) in correlated Rician fading channels. In this paper, we develop a novel approach for performance analysis of L-branch diversity systems in equally correlated Rician fading channels. This approach involves transforming a set of equally correlated branch gains into a set of conditionally independent branch gains, analyzing the performance for the independent case and averaging the conditional results. Consequently, we derive novel expressions for the average error rates of various digital modulations and the output moments for both SC and EGC. We find that the performance of diversity systems in correlated Rician fading channels can be worse than that in correlated Rayleigh fading channels, which has never been observed for the independent fading case.**

***Keywords:* Diversity, equal gain combining, Rician fading, selection combining.**

I. Introduction

This paper derives novel analytical results for the L-branch SC and EGC performance in correlated Rician fading channels. The Rician distribution for the fading amplitudes of received signals where line-of-sight (LOS) propagation exists [1]–[4] can be used to model both microcellular channels and mobile satellite channels. The performance of SC and EGC in *independent* Rician fading channels are available [5]–[7] in the literature. For example, Abu-Dayya and Beaulieu [5] investigate the EGC performance in independent Rician fading channels using an infinite series approximation for the probability density function (pdf) of its output signal-to-noise ratio (SNR). Annamalai *et al.* [6], [7] use the Parseval theorem to evaluate the error rate performance of EGC.

However, the fading among several diversity branches may not be independent for many real-life applications [8], [9]. Residual correlations among diversity branches may exist due to insufficient antenna spacing. Hence, quantitative analysis of diversity gain loss due to correlated fading is important from a theoretical and practical standpoint. While comprehensive theoretical performance results for maximal ratio combining (MRC) systems in various correlated fading channels are available, by comparison, they are scarce for L-branch ($L > 2$) SC and EGC. Indeed, not many published papers consider the SC and EGC performance in correlated Rician fading. Accordingly, in the extensive list of papers dealing with SC and EGC, we have been able to find only one paper that addresses L-branch SC in correlated Rician fading channels. Zhang and Lu [10] derive a general approach to analyze the L-branch SC performance in correlated fading, an approach using L-dimensional integration. The basic idea behind this approach is to express the joint pdf as an L-dimensional inverse integral of the joint characteristic function (chf). For large L (> 3), this method is fairly complicated. To the best of our knowledge, no results have ever been reported for the L-branch coherent EGC performance in correlated Rician fading channels.

Constant correlation model has been studied for L-branch MRC in Nakagami-m fading channels by Aalo [11]. This model may be valid for a set of closely placed antennas and be used as a worst-case benchmark or as a rough approximation by replacing every ρ_{jk} ($j \neq k$) in the correlation matrix with the average value of ρ_{jk} ($j \neq k$). Recently, Chen and Tellambura [12], [13] have developed a new approach for performance analysis of diversity combiners in equally correlated Rayleigh fading channels. They transform a set of equally correlated Rayleigh random variables (RVs) into a set of conditionally independent Rician RVs using a novel representation of the channel gains. In this paper, we generalize their results [12], [13] to equally correlated Rician fading channels. We evaluate the error rate performance and the output moments of L-branch SC and EGC receivers using this approach. Numerical and semi-analytical simulation results show that the performance of diversity systems in correlated Rician fading channels can be worse than that in correlated Rayleigh fading channels.

This paper is organized as follows. Section 2 develops a new channel gain representation for the equally correlated Rician fading. Section 3 evaluates the average error rates of a wide class of digital modulations with SC and EGC. Section 4 derives the moments of the SC and EGC output SNRs. Section 5 presents numerical results for the performance of SC and EGC in equally correlated Rician fading channels and concludes this paper.

II. System and Channel Model

Consider a diversity combining system with L branches. We assume that the channel fading at each branch is frequency non-selective and changes slowly with equally correlated Rician distributed envelop statistics. The received signal at the k-th diversity branch can be expressed as

$$r_k = g_k s + n_k \tag{1}$$

where $g_k = \alpha_k e^{-i\phi_k}$ is the channel gain associated with the k-th branch, $i = \sqrt{-1}$, s is the transmitted signal with energy per symbol E_s and n_k is additive white Gaussian noise (AWGN) with identical power spectral density $\frac{N_0}{2}$ per dimension. The noise components are independent of the signal components and uncorrelated with each other. Hence, we may write the output SNRs of L-branch SC and EGC receivers as

$$\gamma_{sc} = \frac{E_s}{N_0} \max(\alpha_1^2, \alpha_2^2, \cdots, \alpha_L^2) \tag{2a}$$

$$\gamma_{egc} = \frac{E_s}{LN_0} (\alpha_1 + \alpha_2 + \cdots + \alpha_L)^2. \tag{2b}$$

Assuming that the Rice factors at different diversity branches are identical, we develop a new representation for the equally correlated Rician channel gains using a set of L complex Gaussian RVs

$$\begin{aligned} G_k = &\left(\sqrt{1-\rho}\, X_k + \sqrt{\rho}\, X_0 + m_1\right) \\ &+ i\left(\sqrt{1-\rho}\, Y_k + \sqrt{\rho}\, Y_0 + m_2\right) \end{aligned} \tag{3}$$

where $k \in \{1, \ldots, L\}$, $0 < \rho < 1$, $m_1 + im_2$ is the LOS component, $\{X_k\}$ and $\{Y_k\}$, $(k \in \{0, 1, \cdots, L\})$, are two sets of independent zero-mean Gaussian RVs with identical variance $E(|X_k|^2) = E(|Y_k|^2) = \frac{1}{2}$. That is, for any $j, k \in \{0, \ldots, L\}$, $E(X_k Y_j) = 0$ and $E(X_k X_j) = E(Y_k Y_j) = 0$ for $k \neq j$. The validity of (3) for positive ρ only may at first seem a significant limitation. However, the entire range for ρ is between $-\frac{1}{L-1}$ and 1 (the lower limit follows from the positive-definiteness constraint on the covariance matrix). For large L, we may therefore ignore $-\frac{1}{L-1} \leq \rho < 0$.

Since G_k's are non-zero mean complex Gaussian distributed, the amplitudes of the corresponding channel gains α_k's, i.e., $\alpha_k = |G_k|$, are Rician distributed with the Rice factor and the mean square value given respectively by

$$K = m_1^2 + m_2^2 \tag{4a}$$

$$\Omega = E(\alpha_k^2) = 1 + K. \tag{4b}$$

Hence, the average branch SNR is given by

$$\bar{\gamma}_c = \frac{E_s}{N_0} E(\alpha_k^2) = (1+K)\frac{E_s}{N_0} \tag{5}$$

The cross-correlation coefficient between any G_k and G_j ($k \neq j$) equals to

$$\frac{E\{[G_k - E(G_k)][G_j^* - E(G_j^*)]\}}{\sqrt{E[|G_k - E(G_k)|^2] E[|G_j - E(G_j)|^2]}} = \rho \tag{6}$$

where x^* denotes conjugate of x. Eq. (6) specifies the correlation (fading correlation) between two underlying complex Gaussian samples. However, it is required to relate this to the power correlation (i.e. the correlation between α_k^2 and α_j^2). For Rician fading channels, we use [14, Eq. (2.4-9)] to obtain the power correlation as

$$\rho_\eta = \rho \frac{2K + \rho}{2K + 1}. \tag{7}$$

For Rayleigh fading channels ($K = 0$), the fading correlation equals to the square root of power correlation [11], that is

$$\rho_\eta = \rho^2. \tag{8}$$

Eqs. (3) and (7) represent a set of equally correlated Rician envelopes with a specified value of power correlation.

Next, we introduce a 'trick' that enables performance analysis. We consider $X_0 = x_0$ and $Y_0 = y_0$ to be fixed in (3) and let $U = \left(X_0 + m_1/\sqrt{\rho}\right)^2 + \left(Y_0 + m_2/\sqrt{\rho}\right)^2$. Then α_k becomes a set of independent Rician RVs with the Rician factor and the mean square value given respectively by

$$K_f = \frac{\rho u}{1 - \rho} \tag{9a}$$

$$\Omega_f = E(\alpha_k^2 | u) = 1 - \rho + \rho u. \tag{9b}$$

Note that U is noncentral chi-square distributed with 2 degrees of freedom and noncentrality parameter K/ρ, and its pdf is given by [15]

$$p(u) = e^{-\left(\frac{K}{\rho} + u\right)} I_0\left(2\sqrt{\frac{Ku}{\rho}}\right), \quad u \geq 0, \tag{10}$$

where $I_0(x)$ is zero-order modified Bessel function of the first kind.

Performance analysis can now be carried out in two steps. First, conditional performance results are obtained for a set of conditionally independent Rician channel gains and the conditional results are functions of u. Second, the conditional results are averaged over the distribution of U.

III. Average Error Rate Performance

Using the channel gain representation (3), we evaluate the error rate performance of SC and EGC in equally correlated Rician fading channels.

A. Selection Combiner

When $X_0 = x_0$ and $Y_0 = y_0$ are fixed, $\{\alpha_k^2\}$ is a set of independent noncentral chi-square distributed RVs with 2 degrees of freedom and noncentrality parameter ρu, whose cumulative distribution function (cdf) is given by [15, Eq. (2-1-145)].

First, evaluating the cdf of the SC output SNR for a fixed $\left(x_0 + m_1/\sqrt{\rho}\right)^2 + \left(y_0 + m_2/\sqrt{\rho}\right)^2 = u$, we obtain the conditional cdf as

$$F_{\gamma_{sc}|U}(y\,|u) = \left[1 - Q\left(\sqrt{\frac{2\rho u}{1-\rho}}, \sqrt{\frac{2(1+K)y}{\bar{\gamma}_c(1-\rho)}}\right)\right]^L \tag{11}$$

where $Q(a, b)$ is the first order Marcum Q-function defined as [16, Eq. (1)].

Secondly, averaging the conditional cdf (11) over the distribution of U (10), we obtain the output cdf of SC in equally correlated Rician fading as

$$F_{\gamma_{sc}}(y) = e^{-\left(\frac{K}{\rho}\right)} \int_0^\infty \left[1 - Q\left(\sqrt{\frac{2\rho u}{1-\rho}}, \sqrt{\frac{2(1+K)y}{\bar{\gamma}_c(1-\rho)}}\right)\right]^L \times e^{-u} I_0\left(2\sqrt{\frac{Ku}{\rho}}\right) du. \tag{12}$$

As expected, when $K = 0$, (12) reduces to [12, Eq. (13)] for equally correlated Rayleigh fading case.

The average error rates of various digital modulations with a certain diversity combining system can be obtained directly from its output cdf as [17]

$$\bar{P}_s = \int_0^\infty F_{\gamma_{out}}(\gamma) H(\gamma)\, d\gamma \tag{13}$$

where $F_{\gamma_{out}}(\gamma)$ is the output cdf of the diversity combiner and $H(\gamma) = -\frac{dP_s(\gamma)}{d\gamma}$ is the negative derivative of the conditional error probability (CEP), which can be found in [17].

Using (12) with (13), we may evaluate the average error rates of various modulations with L-branch SC as a two-fold integral of well-known functions. For example, the average bit error rate (BER) of differential binary phase-shift-keying (DBPSK) can be obtained as

$$\bar{P}_b = \frac{e^{-\frac{K}{\rho}}}{2} \int_0^\infty \int_0^\infty \left[1 - Q\left(\sqrt{\frac{2\rho u}{1-\rho}}, \sqrt{\frac{2(1+K)\gamma}{\bar{\gamma}_c(1-\rho)}}\right)\right]^L \times e^{-(u+\gamma)} I_0\left(2\sqrt{\frac{Ku}{\rho}}\right) du\, d\gamma \tag{14}$$

which can be readily evaluated by common mathematical software such as Matlab.

B. Equal Gain Combiner

Recall that when $X_0 = x_0$ and $Y_0 = y_0$ are fixed, $\{\alpha_k\}$ is a set of independent Rician RVs. Here we use the chf-based approach to evaluate the error rate performance of L-branch EGC [6]. The CEP for a fixed $\left(x_0 + m_1/\sqrt{\rho}\right)^2 + \left(y_0 + m_2/\sqrt{\rho}\right)^2 = u$ can be evaluated using [6]

$$P_s(u) = \frac{2}{\pi} \int_0^{\pi/2} \frac{\Psi(\tan\zeta|u)}{\sin(2\zeta)}\, d\zeta \tag{15}$$

where $\Psi(\omega) = \mathrm{Re}[\omega G(\omega)\phi_x^*(\omega)]$ and $\mathrm{Re}(x)$ denotes the real part of x. $G(\omega)$ is the Fourier transform of generic conditional error probability which can be found [6, Eqs. (11,13,16,17,19)] for various digital modulations and $\phi_x(\omega)$ is the chf of the square root of the output SNR ($x = \sqrt{\gamma_{egc}}$) given by [6]

$$\phi_x(\omega|u) = \left[\frac{e^{-\frac{\rho u}{1-\rho}}}{\pi} \int_0^\pi e^{\left(i\frac{\omega\xi_k}{2} + \sqrt{\frac{\rho u}{2(1-\rho)}}\cos\theta\right)^2} \times D_{-2}\left(-i\omega\xi - \sqrt{\frac{2\rho u}{1-\rho}}\cos\theta\right) d\theta\right]^L \tag{16}$$

where $\xi = \sqrt{\frac{(1-\rho)\bar{\gamma}_c}{2L(1+K)}}$ and $D_{-2}(x)$ is parabolic cylinder function defined as [18, Eq. (9.240)].

Averaging the conditional error rates (15) over the distribution of U (10), we obtain the average error rates as

$$\bar{P}_s = \frac{2e^{-\frac{K}{\rho}}}{\pi} \int_0^\infty e^{-u} I_0\left(2\sqrt{\frac{Ku}{\rho}}\right) \times \int_0^{\pi/2} \frac{\Psi(\tan\zeta|u)}{\sin(2\zeta)}\, d\zeta\, du. \tag{17}$$

Therefore, we may evaluate the average error rates of digital modulations with L-branch EGC using [6, Eq. (11)] and (16) with (17). For example, the BER of DBPSK can be obtained as

$$\bar{P}_s = \frac{2e^{-\frac{K}{\rho}}}{\pi} \int_0^\infty e^{-u} I_0\left(2\sqrt{\frac{Ku}{\rho}}\right) \int_0^{\pi/2} \mathrm{Re}\left\{\frac{\tan\zeta}{2}\left[\frac{\sqrt{\pi}}{2} \times e^{-\frac{\tan^2\zeta}{4}} + iF\left(\frac{\tan\zeta}{2}\right)\right]\phi_x^*(\tan\zeta|u)\right\} \frac{d\zeta du}{\sin(2\zeta)}. \tag{18}$$

where $\phi_x(\omega|u)$ is given by (16) and $F(x)$ denotes the Dawson integral [19].

IV. Output Moments

As an alternative to error rate analysis, performance measures based on the moments of a combiner output SNR can be used. However, only the mean output SNR is not sufficient and the higher order moments can furnish additional information for system design [20]. For example, the Chebyshev inequality yields $\Pr(|X - \mu| > t) < \sigma_X^2/t^2$ where $E(X) = \mu$. Thus, if X is taken to be the output of a diversity combiner, a large variance indicates that the output is more likely to fade away from the mean. In this section, we derive the moments of the SC and EGC output SNRs in equally correlated Rician fading channels.

A. Selection Combiner

Differentiating the output cdf of SC (12) yields the corresponding output pdf as

$$p_{\gamma_{sc}}(y) = \frac{L(1+K)}{\bar{\gamma}_c} e^{-\left(\frac{K}{\rho} + \frac{(1+K)y}{\bar{\gamma}_c(1-\rho)}\right)} \int_0^\infty e^{-u} \times I_0\left(2\sqrt{\frac{Ku(1-\rho)}{\rho}}\right) I_0\left(2\sqrt{\frac{(1+K)\rho y u}{\bar{\gamma}_c(1-\rho)}}\right) \times \left[1 - Q\left(\sqrt{2\rho u}, \sqrt{\frac{2(1+K)y}{\bar{\gamma}_c(1-\rho)}}\right)\right]^{L-1} du. \tag{19}$$

When $K = 0$, (19) is equivalent to the previous result [12, Eq. (16)].

The moments of the output SNR can then be determined as

$$\begin{aligned} E(\gamma_{sc}^n) &= \int_0^\infty y^n p_{\gamma_{sc}}(y)\, dy \\ &= \left(\frac{\bar{\gamma}_c}{1+K}\right)^n L(1-\rho)^{n+1} e^{-K/\rho} \int_0^\infty y^n e^{-y} \\ &\quad \times \int_0^\infty e^{-u} I_0(2\sqrt{Ku(1-\rho)/\rho}) I_0(2\sqrt{\rho y u}) \\ &\quad \times [1 - Q(\sqrt{2\rho u}, \sqrt{2y})]^{L-1}\, du\, dy. \end{aligned} \tag{20}$$

Using (20), we can readily derive some useful measures such as skewness, kurtosis [21] and the amount of fading [22]. For brevity, we do not develop such results here.

B. Equal Gain Combiner

Using the multinomial expansion, the moments of the EGC output SNR can be written as

$$
\begin{aligned}
E(\gamma_{egc}^n) &= \left(\frac{E_s}{LN_0}\right)^n E[(\alpha_1+\alpha_2+\ldots+\alpha_L)^{2n}] \\
&= \left(\frac{\bar{\gamma}_c}{L}\right)^n \sum_{\substack{k_1,\ldots,k_L=0 \\ k_1+\ldots+k_L=2n}}^{2n} \frac{(2n)!}{\prod_{j=1}^{L} k_j!} E\left(\prod_{j=1}^{L} \alpha_j^{k_j}\right).
\end{aligned} \tag{21}
$$

The joint moments $E(\alpha_1^{k_1}\ldots\alpha_L^{k_L})$ are required here. Unfortunately, these are not known when α_k's are correlated. Our approach (9) appears to be the only way of evaluating these moments. Evaluating the moments of the EGC output SNR for a fixed $\left(x_0+m_1/\sqrt{\rho}\right)^2+\left(y_0+m_2/\sqrt{\rho}\right)^2=u$ and then averaging the conditional results over the distribution of U, we obtain the moments of the EGC output SNR in equally correlated Rician fading channels as

$$
\begin{aligned}
E(\gamma_{egc}^n) = &\left(\frac{\bar{\gamma}_c(1-\rho)}{(1+K)L}\right)^n (2n)! \sum_{\substack{k_1,\ldots,k_L=0 \\ k_1+\ldots+k_L=2n}}^{2n} \Bigg[e^{-\frac{K}{\rho}} \\
&\times \prod_{j=1}^{L}\left(\frac{\Gamma(1+k_j/2)}{k_j!}\right)\int_0^\infty I_0\left(2\sqrt{\frac{Ku}{\rho}}\right) \\
&\times \prod_{j=1}^{L}\Phi\left(-\frac{k_j}{2},1;-\frac{\rho u}{1-\rho}\right)du\Bigg]
\end{aligned} \tag{22}
$$

where $\Gamma(x)$ is the gamma function and $\Phi(a,c;z)$ is the confluent hypergeometric function defined as [18, Eq. (9.210)].

For equally correlated Rayleigh fading channels ($K=0$), using [7, Eq. (C.1)], (22) can be simplified as

$$
\begin{aligned}
E(\gamma_{egc}^n) = &\left(\frac{\bar{\gamma}_c(1-\rho)}{L}\right)^n (2n)! \\
&\times \sum_{\substack{k_1,\ldots,k_L=0 \\ k_1+\ldots+k_L=2n}}^{2n} \Bigg[\prod_{j=1}^{L}\left(\frac{\Gamma(1+k_j/2)}{k_j!}\right) \\
&\times \int_0^\infty \prod_{j=1}^{L}\Phi\left(-\frac{k_j}{2},1;-\frac{\rho u}{1-\rho}\right)du\Bigg]
\end{aligned} \tag{23}
$$

To the best of our knowledge, (22) and (23) are new results. Indeed, we are not aware of any published results concerning the moments of the EGC output SNR in correlated Rician fading channels.

V. Numerical Results and Conclusion

In this section, some numerical results are provided to show the impact of equally correlated Rician fading channels on the performance of L-branch SC and EGC. Semi-analytical simulation results are provided as an independent check for our analytical results.

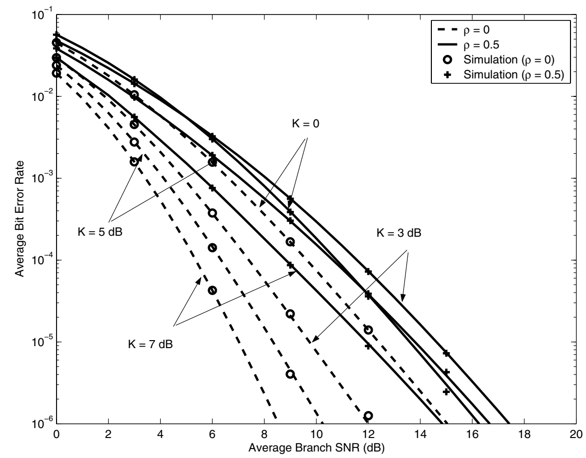

Fig. 1. Average bit error rate of DBPSK with EGC in equally correlated Rician fading channels; $L=4$, $\rho=0,0.5$, $K=0,3dB,5dB,7dB$.

Fig. 1 plots the average BER of DBPSK with 4-branch EGC in equally correlated Rician fading channels for different Rice factors K. The case of $K=0$ represents the equally correlated Rayleigh fading channels. For independent fading ($\rho=0$), EGC always performs better in Rician fading than in Rayleigh fading. For correlated fading, the opposite occurs at the high SNR region. The same unexpected behavior occurs for the SC performance in correlated Rayleigh and Rician fading channels (see Fig. 2). These observations may be explained by using the definition of fading correlation ρ (6). The fading correlation is defined as the correlation between two underlying Gaussian RVs G_k and G_j ($k\neq j$). However, from (7) and (8), we find that for a certain value of ρ, the power correlation ρ_η of Rician fading is larger than that of Rayleigh fading, that is the combined branches are more highly correlated in Rician fading channels. Hence, two opposing mechanisms influence the diversity combiner performance in Rician fading channels. First, the LOS component improves the performance. Second, the larger power correlation than that in Rayleigh fading channels degrades the performance. When the second mechanism dominates, the performance in Rician fading channel can be worse than that in Rayleigh fading channel. In fact, Chang and McLane [23] have observed this situation for square-law combiners.

Fig. 2 shows the impact of fading correlation ρ on the average BER performance of DBPSK with 4-branch SC in equally correlated Rician fading channels. The case of $\rho=0$ represents independent fading. The case of $\rho=1$ represents a single branch case. As ρ increases, the SC performance in both Rayleigh and Rician fading channels degrades. However, the SC performance in Rician fading degrades more rapidly in the low correlation case but more slowly in the high correlation case than that in Rayleigh fading channels. This observation can also be explained by the relationship between the fading correlation ρ and the power correlation ρ_η. As ρ increases, compared with

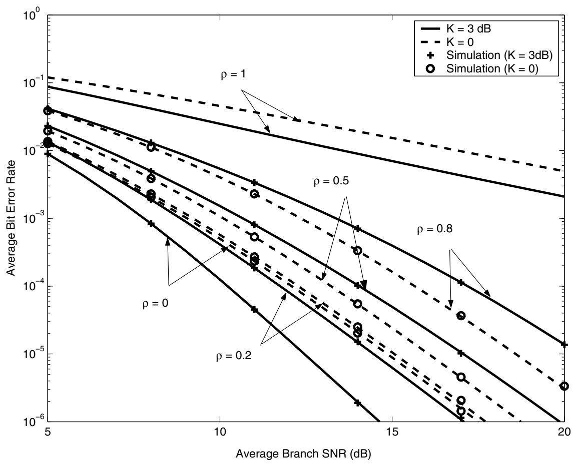

Fig. 2. Average bit error rate of DBPSK with SC in equally correlated Rician fading channels; $L = 4$, $\rho = 0, 0.2, 0.5, 0.8, 1$, $K = 0, 3dB$.

Rayleigh fading case, the ρ_η of Rician fading increases more rapidly when ρ is small but more slowly when ρ is large. That is, Rician fading is more sensitive than Rayleigh fading in the low correlation case, but less sensitive in the high correlation case. We also find that the impact of fading correlation in both Rayleigh and Rician fading is more pronounced at the high SNR region.

In conclusion, a new representation for the equally correlated Rician channel gains has been developed. The error rate performance and the output moments of L-branch SC and EGC in such channels have been derived. Quantitative analysis of EGC is a long-standing problem dating back to 1950s [24]. Even for *independent* fading channels (the distribution problem of a sum of independent Rayleigh variables goes back to Lord Rayleigh himself), the analytical results necessary for comprehensive analysis of EGC with digital modulations appeared only in 1990 [25]. The state of art for L-branch ($L > 2$) EGC in correlated fading is even more limited. Other than computer simulation, no comprehensive analysis techniques have ever been developed. The results of this paper take a modest step in solving the EGC performance problem in correlated fading channels and a much more challenging problem is to extend our results to other correlation models. We also observed that the performance of diversity combiners in correlated Rician fading channels can be worse than that in correlated Rayleigh fading channels.

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