Effects of Rician Fading and Branch Correlation on a Local-Mean-Based Macrodiversity Cellular System[1]

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ABSTRACT In a macrodiversity cellular system, switching radio links between base stations cannot be done instantaneously. Thus branch selection is usually based on the measurement of the slowly-varying local mean power rather than the rapidly-varying instantaneous signal power. In this paper we offer an exact mathematical model to analyze the performance of a local-mean-based macrodiversity cellular system in a shadowed-Rician (desired) /shadowed-Rayleigh (interfering) channel. We investigate the impact of both fading (Rician or Rayleigh) and shadowing in terms of co-channel interference (CCI) probability. We also present an analytical model to incorporate the effects of branch correlation on macrodiversity systems.

I Introduction

Macrodiversity, or a large-scaled space diversity, has long been recognized as an effective tool to combat shadowing [1]. A macrodiversity system serves a mobile station (MS) simultaneously by several base stations (BSs). At any time, the BS with the best quality measure is chosen to serve the MS. The criterion for branch (or BS) selection is a key issue when designing a macrodiversity system. Usually, the branch selection is based on the local mean power rather than the instantaneous power [1, 2, 3, 4], because the branch selection algorithm cannot react to the rapidly varying instantaneous signal power. This paper focuses on $local - mean - based$ branch selection schemes.

Previous studies on macrodiversity systems have evaluated the co-channel interference performance with shadowing only [5, 6, 7] and shadowed Rayleigh fading channels [4]. The co-channel interference performance was also discussed in [9], but it was assumed that the branch selection was based on the instantaneous signal power. The error rate performance of macrodiversity systems has been analyzed in Gaussian noise with both shadowing and Rayleigh (or Nakagami) fading [2, 3, 8]. However, these papers did not consider co-channel interference. To our knowledge, the effect of Rician fading on a local-mean-based macrodiversity system has not been studied before. Furthermore, the effect of branch correlation for macrodiversity systems has not appeared in the literature, either. This paper addresses these issues in detail.

The remainder of this paper is organized as follows. Section II briefly reviews the propagation environment. Section III presents an exact analysis for the performance gain for a local-mean-based macrodiversity system in a shadowed Rician (desired) / shadowed Rayleigh (interfering) channel. This model is extended to incorporate the effect of branch correlation in Section IV. Section V will give some numerical examples, and Section VI has some concluding remarks.

II Microcell Propagation Models

The path loss is assumed to follow the two-slope model so that the area mean received power is

$$\mu = \frac{P_t C}{d^a (1+d/g)^b} \ , \tag{1}$$

where P_t is the transmitted power, C is a constant that incorporates the effects of antenna gain, d is the distance between the transmitter and receiver, g is the break point, a is the basic path loss exponent, and b is the additional path loss exponent.

With log-normal shadowing, the probability density function (pdf) of the *local* mean power, Ω, has the log-normal distribution

$$f_\Omega(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left[\frac{-(\ln x - \ln \mu)^2}{2\sigma^2}\right] \ , \tag{2}$$

where σ is the shadow standard deviation and μ is the *area* mean power determined by the path loss in (1).

In microcell propagation with a dominant light-of-sight (LOS) or specular component, the instantaneous signal amplitude is Rician distributed. If the power in the scattered component of the received signal is σ^2 and the amplitude of the dominant component is A, then the instantaneous received signal power, p, conditioned on the local mean power $\Omega = A^2/2 + \sigma^2$ has the non-central chi-square distribution

$$f_{p|\Omega}(x \mid \Omega) = \frac{K+1}{\Omega} \exp\left[-K - \frac{(K+1)\,x}{\Omega}\right] I_0\left(\sqrt{\frac{4K(K+1)x}{\Omega}}\right) \tag{3}$$

where I_0 is the zero-order modified Bessel function of the first kind, and $K = A^2/2\sigma^2$ is the Rice factor.

An interfering signal usually has no dominant component so that its instantaneous signal amplitude is Rayleigh distributed.

The pdf of the instantaneous interfering signal power, p, in a Rayleigh fading channel can be obtained by letting $K = 0$ in (3), giving

$$f_{p|\Omega}(x \mid \Omega) = \frac{1}{\Omega}\exp\left[-\frac{x}{\Omega}\right] , \quad (4)$$

where Ω is the local mean interfering signal power.

III Co-channel Interference Probability

This section presents an analytical model for calculating the co-channel interference (CCI) probability for an L-branch local-mean-based macrodiversity system with shadowing and fading. Our model assumes that the local mean power of the desired signal, $\Omega_{d,k}$, is available for each branch k, where $k = 1, \ldots, L$. In practice, the desired signal power is mixed with the total interference power for each branch $\Omega_{I,k}$, so that $\Omega_{d,k} + \Omega_{I,k}$ is actually measured. However, the difference is small for large $\Omega_{d,k}/\Omega_{I,k}$. If the branch having the largest $\Omega_{d,k}$ is selected, then the local-mean power of the selected branch is

$$S = \max\left(\Omega_{d,1}, \Omega_{d,2}, \cdots, \Omega_{d,L}\right) . \quad (5)$$

Let $F_k(x)$ and $f_k(x)$ denote the cumulative distribution function (cdf) and the pdf of $\Omega_{d,k}$, respectively. If the $\Omega_{d,k}$ are *independent* random variables with the pdf in (2), then S has the pdf $f_S(y) = L\left[F_k(y)\right]^{L-1} f_k(y)$. The CCI probability is

$$\begin{aligned} P(CI) &= \mathrm{P_r}\left[p_d/p_I < \lambda_{\mathrm{th}}\right] \\ &= 1 - \int_0^\infty \left[\int_{-\infty}^{\frac{x}{\lambda_{\mathrm{th}}}} f_{p_I}(y)dy\right] f_{p_d}(x)dx , \end{aligned} \quad (6)$$

where p_d and p_I are the total powers of the desired and interfering signals for the selected branch with pdfs $f_{p_d}(x)$ and $f_{p_I}(y)$, respectively, and λ_{th} is the protection ratio.

III-A Pure Shadowing

The interfering signals add noncoherently so that the total interference power on the kth branch is $\Omega_{I,k} = \sum_{i=1}^{n} \Omega_{I,k,i}$, where n is the number of interferers and $\Omega_{I,k,i}$ is the power of the ith interferer on the kth branch. It is widely accepted that $\Omega_{I,k}$ can be approximated by a log-normal random variable with area mean power $\mu_{I,k}$ and standard deviation $\sigma_{I,k}$. The parameters $\sigma_{I,k}$ and $\mu_{I,k}$ can be calculated by using a variety of methods, including Schwartz and Yeh's method [10].

If the $\{\Omega_{I,k}\}_{k=1}^{n}$ are independent and identically distributed (iid), and the $\{\Omega_{d,k}\}_{k=1}^{L}$ are also iid and independent of the $\{\Omega_{I,k}\}_{k=1}^{n}$, then [5, 7]

$$\begin{aligned} P(CI) = & \\ & 1 - L\int_0^\infty \left[\int_{-\infty}^{\frac{x}{\lambda_{\mathrm{th}}}} \frac{1}{\sqrt{2\pi}\sigma_I y}\exp\left[\frac{-\left(\ln y - \ln\mu_I\right)^2}{2\sigma_I^2}\right]dy\right] \\ & \times\left[1 - Q\left(\frac{\ln x - \ln\mu_d}{\sigma_d}\right)\right]^{L-1} \\ & \times\frac{1}{\sqrt{2\pi}\sigma_d x}\exp\left[\frac{-\left(\ln x - \ln\mu_d\right)^2}{2\sigma_d^2}\right]dx \end{aligned} \quad (7)$$

where $Q(y) = \int_y^\infty \frac{1}{\sqrt{2\pi}}\exp(-x^2/2)dx$, and σ_d and μ_d are the shadowing standard deviation and area mean power of the desired signal on the kth diversity branch, respectively.

For ease of evaluation, we let $w = (\ln x - \ln\mu_d)/\sqrt{2}\sigma_d$ and transform (7) into a Hermite integration form. That is,

$$P(CI) = 1 - \int_{-\infty}^{\infty} g(w)\exp(-w^2)dw \simeq 1 - \sum_{i=1}^{n} g(w_i)h_i , \quad (8)$$

where

$$\begin{aligned} g(w) &= \frac{L}{\sqrt{\pi}}\left[1 - Q\left(\frac{\sqrt{2}\sigma_d w + \ln\dfrac{\mu_d}{\mu_I\lambda_{\mathrm{th}}}}{\sigma_I}\right)\right] \\ & \quad \left[1 - Q\left(\sqrt{2}w\right)\right]^{L-1} , \end{aligned} \quad (9)$$

and w_i and h_i are the roots and weight factors of the nth-order Hermite polynomial, respectively [13].

III-B Rician Fading and Shadowing

For a local-mean-based macrodiversity system with shadowed Rician fading channels, the branch selection is still based on the best local mean power $\Omega_{d,k}$. If S in (5) is assumed known, then by substituting (3) and (4) into (6) we obtain [7]

$$\begin{aligned} P(CI \mid S, \underline{\Omega}_I) &= \sum_{i=1}^{n} \frac{{\Omega_{I,i}}^{n-1}}{\prod_{j=1,j\neq i}^{n}\left(\Omega_{I,i} - \Omega_{I,j}\right)} \frac{K+1}{K+1+\dfrac{S}{\Omega_{I,i}\lambda_{\mathrm{th}}}} \\ & \quad \exp\left[\frac{-K\dfrac{S}{\lambda_{\mathrm{th}}\Omega_{I,i}}}{K+1+\dfrac{S}{\Omega_{I,i}\lambda_{\mathrm{th}}}}\right] \end{aligned} \quad (10)$$

where $\underline{\Omega}_I = (\Omega_{I,1}, \cdots, \Omega_{I,n})$ and K is the Rice factor of the desired signal. Assuming that the $\{\Omega_{I,k}\}_{k=1}^{n}$ are independent, the joint pdf of $\underline{\Omega}_I$ is

$$f_{\underline{\Omega}_I}(\underline{x}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma_{I,i}x_i}\exp\left[\frac{-\left(\ln x_i - \ln\mu_{I,i}\right)^2}{2\sigma_{I,i}^2}\right] \quad (11)$$

where $\underline{x} = (x_1, \cdots, x_n)$. By using (11), (10), and the pdf of S, we obtain

$$\begin{aligned} P(CI) = & \int_0^\infty \cdots \int_0^\infty P(CI \mid S, \underline{\Omega}_I) \\ & \frac{L\left[1 - Q\left(\frac{\ln S - \ln\mu_d}{\sigma_d}\right)\right]^{L-1}}{\sqrt{2\pi}\sigma_d S}\exp\left[\frac{-\left(\ln S - \ln\mu_d\right)^2}{2\sigma_d^2}\right] \\ & \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma_{I,i}\Omega_{I,i}}\exp\left[\frac{-\left(\ln\Omega_{I,i} - \ln\mu_{I,i}\right)^2}{2\sigma_{I,i}^2}\right] dSd\underline{\Omega}_I . \end{aligned} \quad (12)$$

By using the substitution $\alpha = \ln(S/\mu_d)/(\sqrt{2}\sigma_d)$ and $\beta_i = \ln(\Omega_{I,i}/\mu_{I,i})/(\sqrt{2}\sigma_{I,i})$, $i = 1, \cdots, n$, we transform (12) into a Hermite integration form, which can be evaluated with numerical ease. In particular,

$$\begin{aligned} P(CI) = & \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \frac{L\left[1 - Q\left(\sqrt{2}\alpha\right)\right]^{L-1} G(\alpha, \underline{\beta})}{\sqrt{\pi}^{n+1}} \\ & \exp\left[-\alpha^2 - \sum_{i=1}^{n}\beta_i^2\right] d\alpha \ d\underline{\beta} \end{aligned}$$

$$\simeq \sum_{k_n=1}^{h_n} \cdots \sum_{k_0=1}^{h_0} \frac{L}{\sqrt{\pi}^{n+1}} \left[1 - Q\left(\sqrt{2}x_{k_0}\right)\right]^{L-1} G(x_{k_0}, x_{k_1}, \cdots, x_{k_n}) w_{k_0} \cdots w_{k_n} \quad (13)$$

where $\underline{\beta} = (\beta_1, \cdots, \beta_n)$, x_{k_i} is the root of the h_ith order Hermite polynomial, and w_{k_i} is its corresponding weight factor. Here $G(\alpha, \underline{\beta})$ is obtained by substituting $S = \mu_d \exp(\sqrt{2}\alpha\sigma_d)$ and $\Omega_{I,i} = \mu_{I,i} \exp(\sqrt{2}\beta_i \sigma_{I,i}), i = 1, \cdots, n$, into $P(CI \mid S, \underline{\Omega}_I)$ in (10). That is

$$G(\alpha, \underline{\beta}) = \sum_{i=1}^{n} \frac{1}{\prod_{\substack{j=1 \\ j \neq i}}^{n} \left(1 - \frac{\mu_{I,j}}{\mu_{I,i}} \exp\left[\sqrt{2}(\beta_j \sigma_{I,j} - \beta_i \sigma_{I,i})\right]\right)} \frac{K+1}{K+1+\epsilon_i} \exp\left[\frac{-K\epsilon_i}{K+1+\epsilon_i}\right] \quad (14)$$

where

$$\epsilon_i = \frac{\mu_d}{\lambda_{\text{th}} \mu_{I,i}} \exp\left[\sqrt{2}(\alpha\sigma_d - \beta_i \sigma_{I,i})\right] . \quad (15)$$

IV Correlated Branches

Until now, we have assumed independent shadowing on the macrodiversity branches. This assumption may sometimes be violated because of insufficient spacing of BSs, especially in microcell systems.

For a correlated L-branch macrodiversity system, the joint pdf of $\underline{\Omega}_d$ [12]

$$f_{\underline{\Omega}_d}(\underline{z}) = \frac{\exp\left[-\frac{1}{2} Y^T \mathbf{M}^{-1} Y\right]}{\sqrt{(2\pi)^L \det(\mathbf{M})} z_1 \cdots z_L} \quad (16)$$

where $\underline{z} = (z_1, \cdots, z_L)$, $\mathbf{Y}^T = [y_1, \cdots, y_L]$ denotes the transpose of column vector

$$\mathbf{Y} = \begin{bmatrix} \ln(z_1) - \ln(\mu_1) \\ \vdots \\ \ln(z_L) - \ln(\mu_L) \end{bmatrix} \quad (17)$$

and $\mu_1, \cdots, \mu_L$ are the area means of each diversity branch. The covariance matrix $\mathbf{M}$ is expressed as

$$\mathbf{M} = \begin{bmatrix} \sigma_1^2 & \cdots & \nu_{1L} \\ \vdots & \ddots & \vdots \\ \nu_{L1} & \cdots & \sigma_L^2 \end{bmatrix} \quad (18)$$

where σ_i is the shadowing standard deviation and $\nu_{i,j}$ is the covariance of $\ln(\Omega_{di})$ and $\ln(\Omega_{dj})$

$$\nu_{ij} = \mathrm{E}\left[(\ln(\Omega_{di}) - \ln(\mu_i))(\ln(\Omega_{dj}) - \ln(\mu_j))\right] . \quad (19)$$

It is convenient to define $\mathbf{N} = \mathbf{M}^{-1}$ and express the matrix multiplication in (16) as follows.

$$\mathbf{Y^T N Y} = \sum_{i=0}^{L} \mathbf{N}_{ii} y_i^2 + 2 \sum_{i=0}^{L-1} \sum_{j=i+1}^{L} \mathbf{N}_{ij} y_i y_j \quad (20)$$

where N_{ij} is the element in the ith row and jth column.

According to (5), (16), and (20), the probability that the local mean power S at the output of the combiner being less than y is

$$\Pr(S < y) = \int_{-\infty}^{y} \cdots \int_{-\infty}^{y} \frac{1}{\sqrt{(2\pi)^L \det(\mathbf{M})} z_1 \cdots z_L} \exp\left[-\frac{1}{2}\left(\sum_{i=1}^{L} N_{ii} y_i^2 + 2 \sum_{i=1}^{L-1} \sum_{j=i+1}^{L} N_{ij} y_i y_j\right)\right] d\underline{z} \quad (21)$$

where N_{ij} and y_i are defined in (20) and (17), respectively.

The key for analyzing the CCI probability of the local-mean-based macrodiversity system is to find the pdf of the combiner output power, $f_S(y)$. Unlike the uncorrelated case where there exists a closed-form expression for $f_S(y)$, one can not easily get a simple closed formula for the joint distribution of more than two mutually correlated lognormal random variables. However, for $L = 2$,

$$\begin{aligned} f_S(y) = {} & \frac{1}{\sqrt{2\pi \det(\mathbf{M})}} \left\{ \frac{1}{\sqrt{N_{22}}} \exp\left[-\frac{y^2}{2}\left(N_{11} - \frac{N_{12}}{N_{22}}\right)\right] \left[1 - Q\left(\left(\sqrt{N_{22}} + \frac{N_{12}}{\sqrt{N_{22}}}\right) y\right)\right] \right. \\ & \left. + \frac{1}{\sqrt{N_{11}}} \exp\left[-\frac{y^2}{2}\left(N_{22} - \frac{N_{12}}{N_{11}}\right)\right] \left[1 - Q\left(\left(\sqrt{N_{11}} + \frac{N_{12}}{\sqrt{N_{11}}}\right) y\right)\right] \right\} \end{aligned} \quad (22)$$

where $y = (\ln p_{od} - \ln \Upsilon_d)$ and d denotes the branch selected by the macrodiversity system. Consider the following covariance matrix $\mathbf{M}$

$$\mathbf{M} = \begin{bmatrix} \sigma^2 & \mu \\ \mu & \sigma^2 \end{bmatrix} , \quad (23)$$

and

$$\mathbf{N} = \mathbf{M}^{-1} = \frac{1}{\sigma^4 - \mu^2} \begin{bmatrix} \sigma^2 & -\mu \\ -\mu & \sigma^2 \end{bmatrix} . \quad (24)$$

By substituting (24) into (22), we express the pdf of the output local-mean power of the dual macrodiversity system as

$$f_S(y) = \frac{\sqrt{2}}{\sqrt{\pi}\sigma y} \left\{ 1 - Q\left[\left(\frac{1-r}{\sqrt{1-r^2}}\right)\left(\frac{\ln y - \ln \mu_d}{\sigma}\right)\right] \exp\left[-\frac{(\ln y - \ln \mu_d)^2}{2\sigma^2}\right] \right\} \quad (25)$$

where the correlation coefficient r is defined as $r = \dfrac{\nu}{\sigma^2}$. Combining (10), (11), and (25), we obtain

$$\begin{aligned} P(CI) & = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \frac{2G(\alpha, \underline{\beta})}{\sqrt{\pi}^{n+1}} \left[1 - Q\left(\sqrt{2}\left(\frac{1-r}{\sqrt{1-r^2}}\right)\alpha\right)\right] \exp\left[-\alpha^2 - \sum_{i=1}^{n} \beta_i^2\right] d\alpha \; d\underline{\beta} \\ & \simeq \sum_{k_n=1}^{h_n} \cdots \sum_{k_0=1}^{h_0} \frac{2\left[1 - Q\left(\sqrt{2}\left(\frac{1-r}{\sqrt{1-r^2}}\right) x_{k_0}\right)\right]}{\sqrt{\pi}^{n+1}} \times G(x_{k_0}, \cdots, x_{k_n}) w_{k_0} \cdots w_{k_n} , \end{aligned} \quad (26)$$

where α and $\underline{\beta}$ are defined in (13), the weight factor w_{k_i} of the h_ith order Hermite polynomial can be found in [13], and $G(\alpha, \underline{\beta})$ is defined in (14).

V Numerical Results

We consider a cellular system with nine cells per cluster. In this case, two co-channel interferers are at 5.2 R, where R is the cell radius. Assume the mobile unit is on the boundary of the cell with a distance of R to the base station. Consider a dual slope path loss model with $a = b = 2$ and $g = 0.15$ in (1). Fig. 1 (a), (b), and (c) illustrate the gain achieved by a local-mean-based $S-$ macrodiversity system over a shadowed-Rician (desired) /shadowed-Rayleigh (interfering) channel for the Rice factors $K = -\infty$, 7, and 20 dB. Table 1 lists the threshold λ_{th} and diversity gain (D.G.) in terms of 5 % co-channel interference (CCIP) probability. Some general observations can be made: 1) a higher shadowing spread leads to a higher diversity gain and a lower required threshold λ_{th}; 2) the diversity gain per branch is decreased as the number of diversity branches is increased; 3) the diversity gain increases with the requirement of the system, e.g., the diversity gain for 5 % CCI probability is higher than that for 10 % CCI probability. In addition, we see that the diversity *gain* seems to be affected little by fading and that a shadowed Rayleigh channel has the least diversity gain.

We evaluate the effects of correlation coefficient r on a 2-branch macrodiversity system with $\sigma = 6$ dB and various K, $K = -\infty$ dB (Fig. 2 (a)); $K = 10$ dB (Fig. 2 (b)). Observe that as r approaches one, the diversity gain becomes zero. Furthermore, for $r = 0.7$, the diversity gain will be reduced to about 50 % of the gain when $r = 0$.

VI Concluding Remarks

We consider a cellular system with nine cells per cluster. This paper presented an analytical model for calculating the co-channel interference probability of a local-mean-based macrodiversity system in a shadowed Rician (desired) / shadowed Rayleigh (interfering) channel. Compared to a pure shadowing channel, Rayleigh fading degrades the S/I performance by about 4 $\sim$ 5 dB at 10 % CCI probability. However, as the Rice factor K gets large, the degradation of S/I is within 1 dB. We also observe that fading (either Rayleigh or Rician) has little effect on the *diversity gain* of local-mean-based macrodiversity systems. The diversity gain is the same, but Rayleigh fading is always worse than Rician fading.

In two-branch macrodiversity system, a branch correlation coefficient of $r = 0.7$ will reduce the diversity gain by 50 %. We considered correlated shadowing between diversity branches, but shadowing components between the desired and interfering signals are assumed to be independent in this paper. Furthermore, it has been shown that the correlation of shadowing components between interferers does not significantly influence the CCI probability performance [11]. The results obtained in this paper will be close to the results derived for the environment with multiple correlated log-normal shadowing interferers.

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Table 1: Macrodiversity gain (D. G.) and the threshold λ_{th} of S/I set at the receiver in terms of 5 % co-channel interference probability (CCIP) over a channel with both shadowing and Rician fading $K = -\infty$, 7, 20 dB.

	$\sigma = 6$ dB					
L	$K = -\infty$ dB		$K = 7$ dB		$K = 20$ dB	
	λ_{th}	D. G.	λ_{th}	D. G.	λ_{th}	D. G.
1	5.49	-	9.34	-	10.86	-
2	9.78	4.29	13.81	4.47	15.56	4.70
3	11.78	6.29	16.11	6.77	17.51	6.65
4	13.13	7.64	17.47	8.13	19.10	8.24

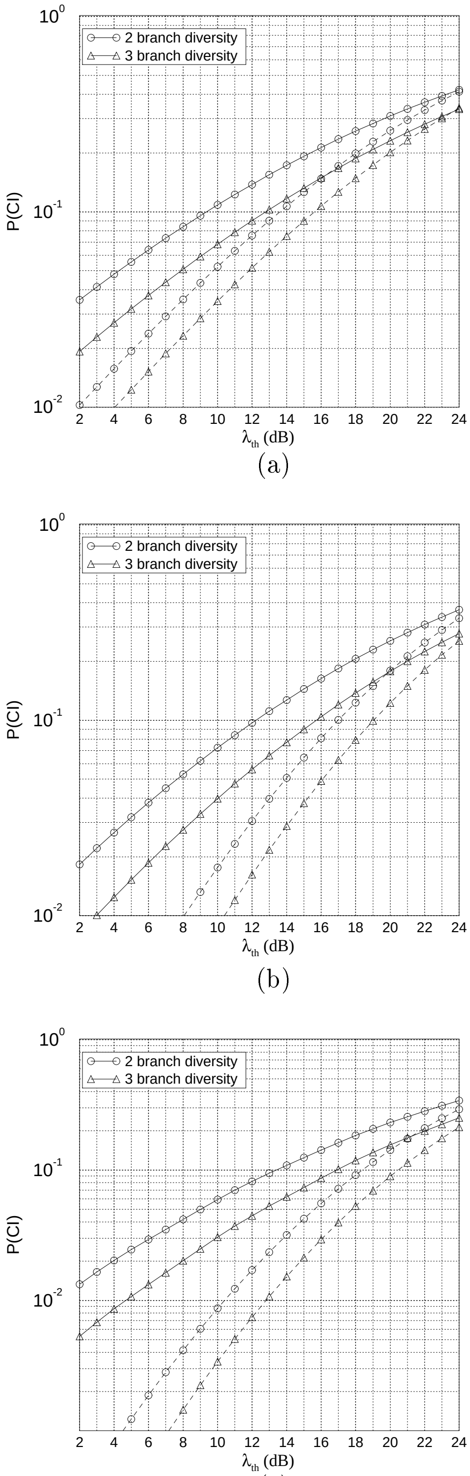

Figure 1: The CCI probability, $P(CI)$, against the required threshold, $\lambda_{\rm th}$, at the receiver for the local-mean-based macrodiversity system over the shadowed-Rician (desired) / shadowed-Rayleigh (interfering) channel with Rice factor (a) $K = -\infty$ dB, (b) $K = 7$ dB, and (c) $K = 20$ dB, where the solid lines (——) denote the case for shadowing standard deviation $\sigma = 10$ dB and the dashed lines $(---)$ for $\sigma = 6$ dB; $a = b = 2$, $g = 0.15$R; two interferers are located at a distance of 5.2R.

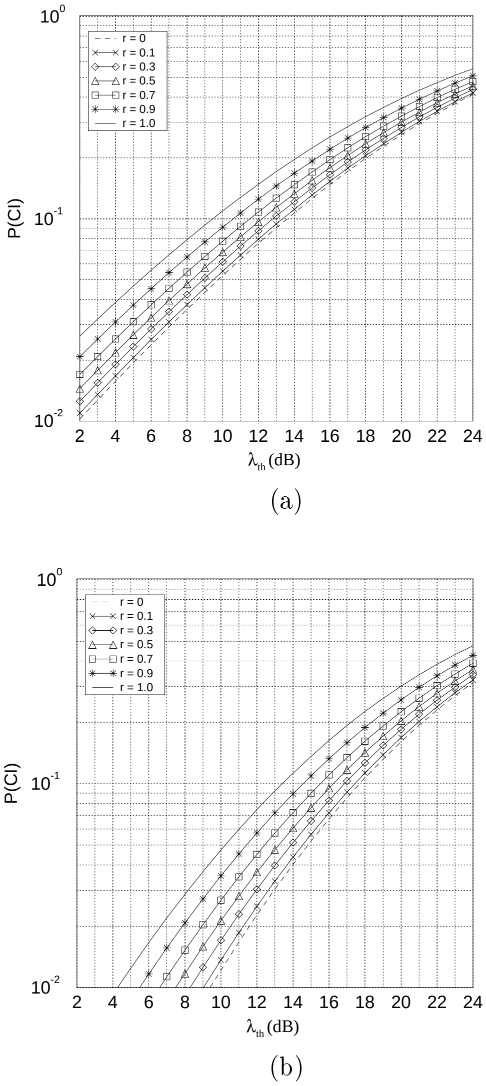

Figure 2: Effect of branch correlation coefficient r on the local-mean-based macrodiversity system with Rice factor (a) $K = -\infty$ dB and (b) $K = 10$ dB, where $\sigma = 6$ dB; $a = b = 2$, $g = 0.15$R; two interferers are located at a distance of 5.2R.