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

Li-Chun Wang, *Member, IEEE,* Gordon L. Stüber, *Fellow, IEEE,* and Chin-Tau Lea

***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 cochannel interference (CCI) probability. We also present an analytical model to incorporate the effects of branch correlation on macrodiversity systems.**

***Index Terms*— Cellular radio system, cochannel interference, macrodiversity, Nakagami fading, Rician fading, shadowing.**

I. Introduction

MACRODIVERSITY, or a large-scaled space diversity, has long been recognized as an effective tool to combat shadowing [1], [2]. A macrodiversity system serves a mobile station (MS) simultaneously by several base stations (BS's). 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], [3]–[7] 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 cochannel interference performance with shadowing only [8]–[10] and shadowed Rayleigh fading channels [7]. The cochannel interference performance was also discussed in [12], 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 [3]–[6], [11]. However, these papers did not consider cochannel interference. To our knowledge, the effect of Rician fading on a local-mean-based macrodiversity system has not been studied before. Furthermore, the correlation effect of the wanted signal at different branches of a macrodiversity system 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.

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II. Microcell Propagation Models

The path loss is assumed to follow the two-slope model so that the area mean received power is [18]

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

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 lognormal shadowing, the probability density function (pdf) of the *local* mean power Ω has the lognormal 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 noncentral chi-square distribution

$$f_{p|\Omega}(x|\Omega) = \frac{K+1}{\Omega} \exp\left[-K - \frac{(K_1)x}{\Omega}\right] \cdot I_0\left(\sqrt{\frac{4K(K+1)x}{\Omega}}\right) \tag{3}$$

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

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

where Ω is the local-mean interfering signal power.

III. Cochannel Interference Probability

This section presents an analytical model for calculating the cochannel 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 $k = 1, \cdots, L$. 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

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

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 $f_S(y) = L[F_k(y)]^{L-1} f_k(y)$. The CCI probability is

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

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

A. Pure Shadowing

The interfering signals add noncoherently so that the total interference power on the kth branch is $\Omega_{I,k} = \Sigma_{i=1}^n \Omega_{I,k,i}$, 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 lognormal 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's and Yeh's method [20].

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 [8], [10]

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

where $Q(y) = \int_y^\infty (1/\sqrt{2\pi}) \exp(-x^2/2)\, dx$ 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,

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

where

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

and w_i and h_i are the roots and weight factors of the nth-order Hermite polynomial, respectively [10].

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 [10]

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

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

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

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

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

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

$$P(CI) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \frac{L[1-Q(\sqrt{2}\alpha)]^{L-1} G(\alpha, \underline{\beta})}{\sqrt{\pi}^{n+1}} \cdot \exp\left[-\alpha^2 - \sum_{i=1}^{n} \beta_i^2\right] d\alpha\, d\underline{\beta}$$
$$\cdot \sum_{k_n=1}^{h_n} \cdots \sum_{k_0=1}^{h_0} \frac{L}{\sqrt{\pi}^{n+1}} [1-Q(\sqrt{2}x_{k_0})]^{L-1} \cdot G(x_{k_0}, x_{k_1}, \cdots, x_{k_n}) w_{k_0} \cdots w_{k_n} \tag{13}$$

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 $P(CI|S, \underline{\Omega}_I)$ in (10). That is,

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

where

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

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 BS's, especially in microcell systems.

For a correlated L-branch macrodiversity system, the joint pdf of $\underline{\Omega}_d$ [22]

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

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

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

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

$$\boldsymbol{M} = \begin{bmatrix} \sigma_1^2 & \cdots & \nu_{1L} \\ \vdots & \ddots & \vdots \\ \nu_{L1} & \cdots & \sigma_L^2 \end{bmatrix} \tag{18}$$

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

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

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

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

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

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

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 $L = 2$

$$f_S(y) = \frac{1}{\sqrt{2\pi \det(\boldsymbol{M})}} \cdot \left\{ \frac{1}{\sqrt{N_{22}}} \exp\left[-\frac{y^2}{2}\left(N_{11} - \frac{N_{12}}{N_{22}}\right)\right] \cdot \left[1 - Q\left(\left(\sqrt{N_{22}} + \frac{N_{12}}{\sqrt{N_{22}}}\right) y\right)\right] + \frac{1}{\sqrt{N_{11}}} \exp\left[-\frac{y^2}{2}\left(N_{22} - \frac{N_{12}}{N_{11}}\right)\right] \cdot \left[1 - Q\left(\left(\sqrt{N_{11}} + \frac{N_{12}}{\sqrt{N_{11}}}\right) y\right)\right] \right\} \tag{22}$$

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

$$\boldsymbol{M} = \begin{bmatrix} \sigma^2 & \mu \\ \mu & \sigma^2 \end{bmatrix} \tag{23}$$

and

$$\boldsymbol{N} = \boldsymbol{M}^{-1} = \frac{1}{\sigma^4 - \mu^2} \begin{bmatrix} \sigma^2 & -\mu \\ -\mu & \sigma^2 \end{bmatrix}. \tag{24}$$

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

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

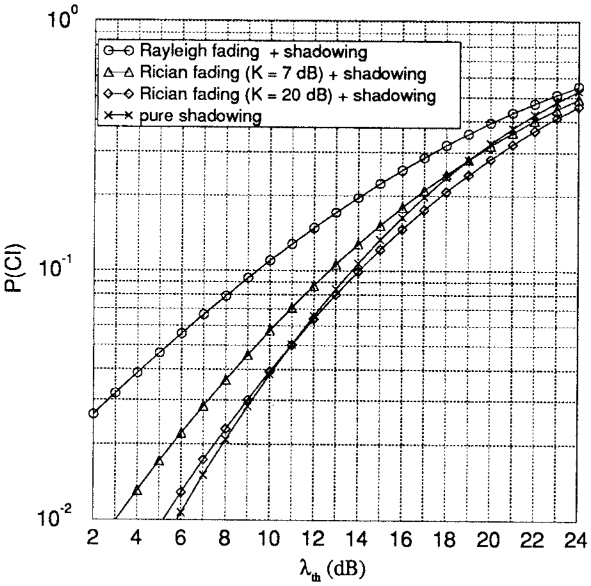


Fig. 1. Comparison of CCI probability $P(CI)$ for no macrodiversity over pure shadowing channels, shadowed Rayleigh channels, and shadowed Rician channels, where $\sigma = 6$ dB and $a = b = 2$ and $g = 0.15R$; two interferers are located at a distance of $5.2R$.

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

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

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 [23], 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 cochannel interferers are at $5.2R$, 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). By letting $L = 1$ in (13) and (8), we show the results of shadowing, Rician fading, and Rayleigh fading in Fig. 1 for the case of no macrodiversity. For 10% CCI, the performance of a shadowed Rayleigh fading channel is about 4 dB worse than a pure shadowing channel. On the other hand, the degradation with Rician fading is less than 1 dB for $K = 7$–20 dB. Surprisingly, Rician fading can sometimes improve the performance when the threshold in receiver is high.

TABLE I
Macrodiversity Gain (D.G.) and the Threshold λ_{th} of S/I Set at the Receiver in Terms of 5% and 10% Cochannel Interference Probability (CCIP) over a Pulse Shadowing Channel

(a) $\sigma = 6$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	10.96	-	13.69	-
2	15.78	4.82	18.12	4.43
3	17.97	7.01	20.46	11.78
4	19.41	8.45	21.80	13.13

(b) $\sigma = 10$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	0.64	-	5.11	-
2	8.54	7.9	12.52	7.41
3	12.22	11.58	16.06	10.95
4	14.36	13.72	18.39	13.28

TABLE II
Macrodiversity Gain (D.G.) and the Threshold λ_{th} of S/I Set At the Receiver in Terms of 5% and 10% Cochannel Interference Probability (CCIP) over a Channel with Both Shadowing and Rayleigh Fading

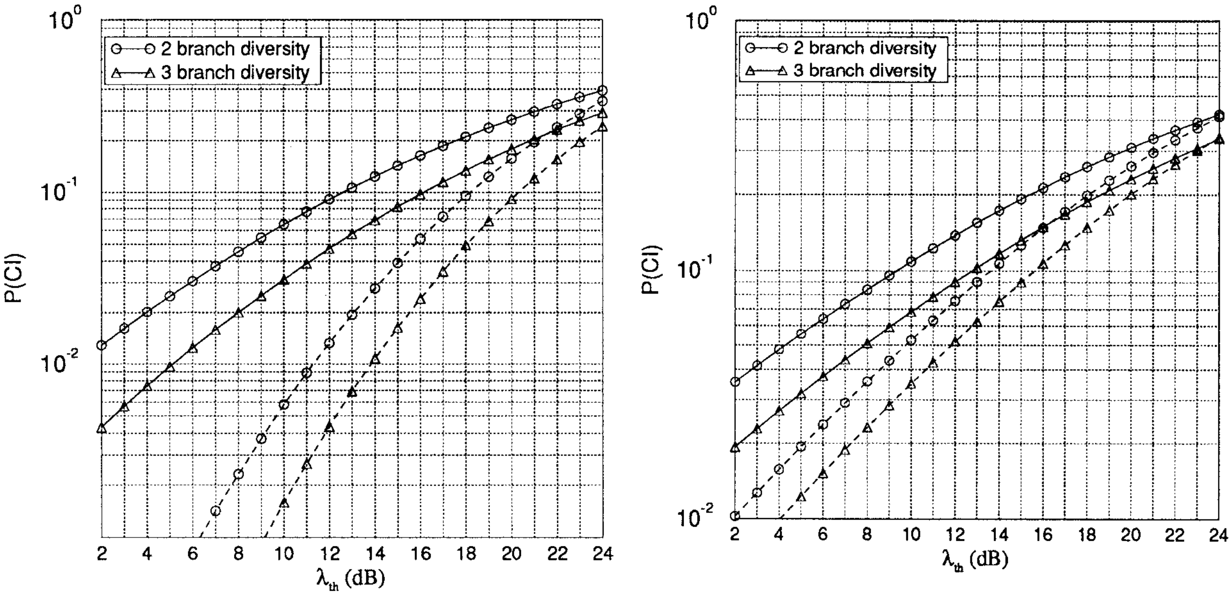
(a) $\sigma = 6$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	5.49	-	9.55	-
2	9.78	4.29	13.54	3.99
3	11.78	6.29	15.51	5.96
4	13.13	7.64	16.80	7.25

(b) $\sigma = 10$ dB

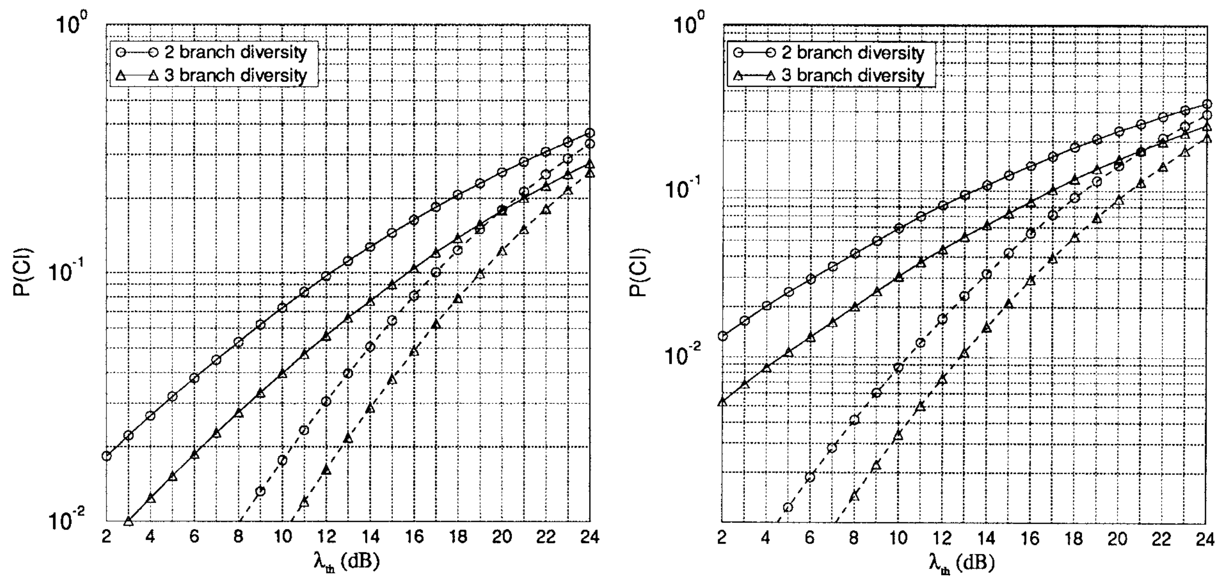
	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	-0.39	-	2.28	-
2	4.27	7.36	9.28	6.96
3	8.00	11.09	12.62	10.34
4	10.23	13.33	15.11	12.83

Fig. 2(a) and (b) shows the CCI probability performance in pure shadowing channels and shadowed Rayleigh channels, respectively. Fig. 3(a) and (b) illustrates the gain achieved by a local-mean-based S-macrodiversity system over a shadowed-Rician (desired)/shadowed-Rayleigh (interfering) channel for the Rice factors $K = 7$ and 20 dB. Tables I–IV list the threshold λ_{th} and diversity gain (D.G.) in terms of 5% and 10% cochannel interference (CCIP) probability. Diversity gain here is defined as the additional S/I (in decibels) that is required by a system without diversity to produce the same CCI 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; and 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



(a) (b)

Fig. 2. The CCI probability $P(CI)$ against the required threshold $\lambda_{\rm th}$ at the receiver for the local-mean-based macrodiversity system over (a) pure shadowing channels and (b) shadowed Rayleigh channels, where the solid lines (——) denote the case for shadowing standard deviation $\sigma = 10$ dB and the dashed lines (- - -) for $\sigma = 6$ dB and $a = b = 2$ and $g = 0.15R$; two interferers are located at a distance of $5.2R$.



(a) (b)

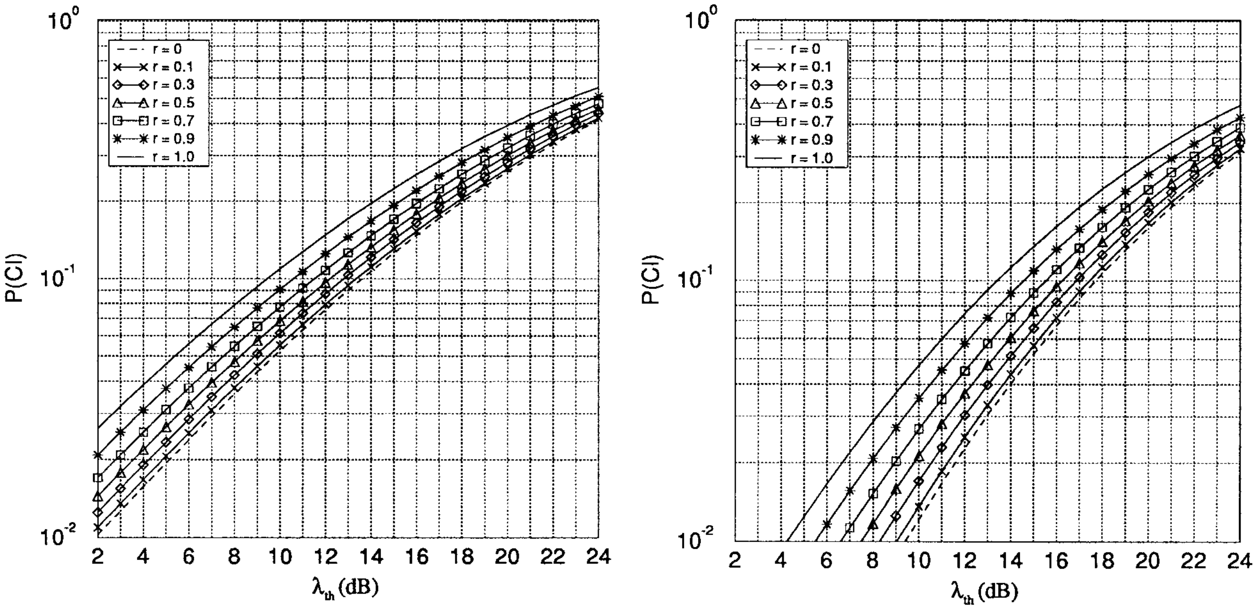
Fig. 3. The CCI probability $P(CI)$ against the required threshold $\lambda_{\rm th}$ at the receiver for the local-mean-based macrodiversity system over the shadowed-Rician (desired)/shadowed-Rayleigh (interfering) channel with Rice factor (a) $K = 7$ dB and (b) $K = 20$ dB, where the solid lines (——) denote the case for shadowing standard deviation $\sigma = 10$ dB and the dashed lines (- - -) for $\sigma = 6$ dB and $a = b = 2$ and $g = 0.15R$; two interferers are located at a distance of $5.2R$.

fading and that a shadowed Rayleigh channel has the least diversity gain.

We evaluate the effects of correlation coefficient r on a two-branch macrodiversity system with various K and $\sigma, K = -\infty$ dB and $\sigma = 6$ dB [Fig. 5(a)]; $K = 10$ dB and $\sigma = 6$ dB [Fig. 4(b)]; $K = -\infty$ dB and $\sigma = 10$ dB [Fig. 5(a)]; $K = 10$ dB and $\sigma = 10$ dB [Fig. 5(b)]. With respect to 10% CCI probability, Table V lists $\lambda_{\rm th}$ with different r. 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 $r = 0$.

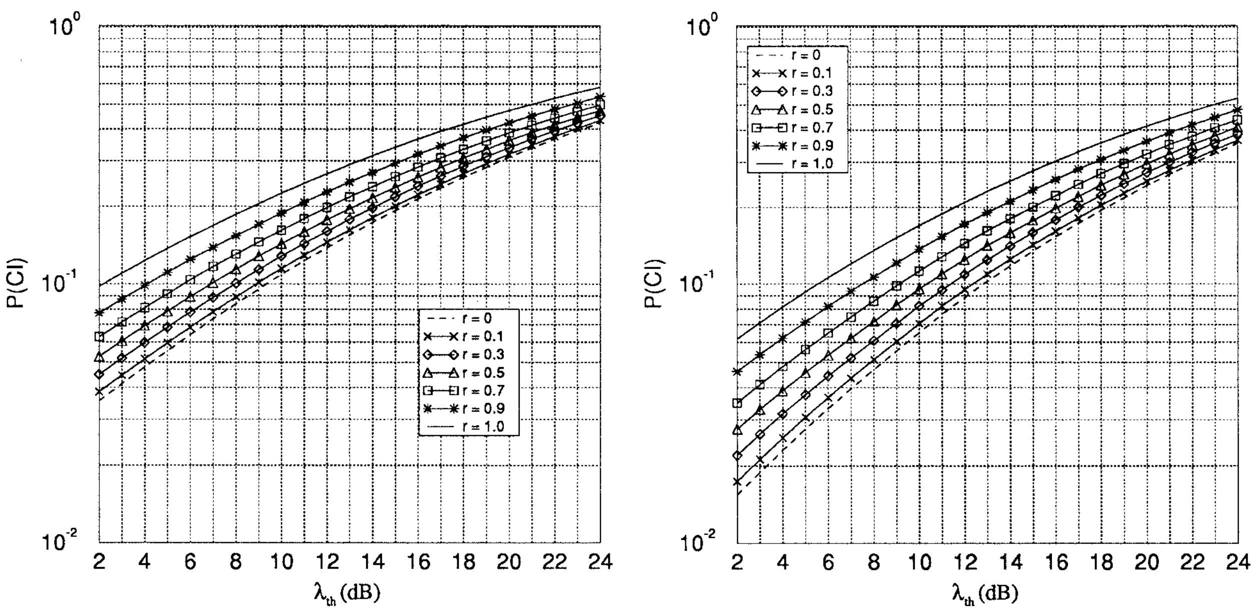
VI. Concluding Remarks

We have presented an analytical model for calculating the cochannel interference probability of a local-mean-based macrodiversity system in a shadowed Rician (desired)/shadowed Rayleigh (interfering) channel. The local-mean-based macrodiversity system is easily implemented in



(a) (b)

Fig. 4. 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 and $a = b = 2$ and $g = 0.15R$; two interferers are located at a distance of $5.2R$.



(a) (b)

Fig. 5. 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 $\sigma = 10$ dB and $a = b = 2$ and $g = 0.15R$; two interferers are located at a distance of $5.2R$.

the sense that it reacts to the slowly varying local-mean power. Based on the proposed analytical model, we analyzed the effect of fading and branch-correlated shadowing of the desired signals on the system performance.

Compared to a pure shadowing channel, Rayleigh fading degrades the S/I performance by about 4–5 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. Finally, for a two-branch macrodiversity system, we show a desired signal shadow branch-correlation coefficient of $r = 0.7$ will reduce the macrodiversity gain by 50%.

There are some other interesting issues that are worthy of further study. For example, the system performance with mutually correlated multiple interferers is not addressed in this paper. Fortunately, it has been shown that the correlation of shadowing components between interferers does

TABLE III
MACRODIVERSITY GAIN (D.G.) AND THE THRESHOLD λ_{th} OF S/I SET AT THE RECEIVER IN TERMS OF 5% AND 10% COCHANNEL INTERFERENCE PROBABILITY (CCIP) OVER A CHANNEL WITH BOTH SHADOWING AND RICIAN FADING $K_d = 7$ dB

(a) $\sigma = 6$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	9.34	–	12.89	–
2	13.81	4.47	16.99	4.10
3	16.11	6.77	19.06	6.17
4	17.47	8.13	20.33	7.44

(b) $\sigma = 10$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	-0.11	–	5.01	–
2	7.40	7.51	12.18	7.17
3	11.24	11.34	15.66	10.65
4	13.62	13.73	17.90	12.89

TABLE IV
MACRODIVERSITY GAIN (D.G.) AND THE THRESHOLD λ_{th} OF S/I SET AT THE RECEIVER IN TERMS OF 5% AND 10% COCHANNEL INTERFERENCE PROBABILITY (CCIP) OVER A CHANNEL WITH BOTH SHADOWING AND RICIAN FADING $K_d = 20$ dB

(a) $\sigma = 6$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	10.86	–	13.16	–
2	15.56	4.70	18.42	4.26
3	17.51	6.65	20.53	6.37
4	19.10	8.24	21.73	7.37

(b) $\sigma = 10$ dB

	5 % CCIP		10 % CCIP	
L	λ_{th}	D. G.	λ_{th}	D. G.
1	1.03	–	6.01	–
2	8.89	7.86	13.37	7.36
3	12.72	11.69	17.10	11.09
4	14.91	13.88	19.04	13.03

TABLE V
EFFECTS OF BRANCH CORRELATION ON A TWO-BRANCH MACRODIVERSITY

(a) $\sigma = 6$ dB

	$K = -\infty$ dB		$K = 10$ dB	
r	λ_{th}	D. G.	λ_{th}	D. G.
0	13.54	3.99	17.75	4.33
0.1	13.39	3.84	17.45	4.03
0.3	12.78	3.23	16.90	3.48
0.5	12.23	2.68	16.26	2.84
0.7	11.46	1.91	15.53	2.11
0.9	10.51	1.02	14.46	1.04
1.0	9.55	–	13.42	–

(b) $\sigma = 10$ dB

	$K = -\infty$ dB		$K = 10$ dB	
r	λ_{th}	D. G.	λ_{th}	D. G.
0	9.24	6.96	12.87	7.37
0.1	8.93	6.65	12.36	6.86
0.3	7.94	5.66	11.37	5.87
0.5	7.0	4.72	10.3	4.8
0.7	5.67	3.39	9.06	3.56
0.9	4.12	1.84	7.39	1.89
1.0	2.28	–	5.50	–

not significantly influence the CCI probability performance [21]. Thus, the results obtained in this paper will be close to the results derived for the environment with multiple correlated lognormally shadowed interferers. On the other hand, better techniques to study the effects of correlated shadowing between the desired signal and the interfering signals are needed.

Finally, this paper assumes that the desired signal power dominates the total received power. Implicitly, each diversity branch operates under the condition that the received desired signal power is stronger than the interference power. This assumption is generally valid for frequency-division multiple-access/time-division multiple-access (FDMA/TDMA) systems, since the purpose of the frequency planning strategy used in FDMA/TDMA systems is to ensure the radio path lengths for the cochannel interferers are significantly longer than those for the desired signals. Consequently, the FDMA/TDMA systems are largely capable of avoiding the situation where the cochannel interference power received at a base station is stronger than that of the desired signal. However, this assumption is not true for a CDMA system. Thus, further research on the performance of CDMA-based macrodiversity systems is needed.

REFERENCES

[1] W. C. Jakes, *Microwave Mobile Communications*. New York: Wiley, 1974.
[2] W. C. Y. Lee, *Mobile Communications Design Fundamentals*. New York: Wiley, 1991.
[3] W. P. Yung, "Probability of bit error for MPSK modulation with diversity reception in Rayleigh fading and lognormal shadowing channel," *IEEE Trans. Commun.*, vol. 38, pp. 933–937, July 1990.
[4] A. M. D. Turkmani, "Performance evaluation of a composite microscopic plus macroscopic diversity system," *Proc. Inst. Elect. Eng.*, vol. 138, pt. I, pp. 15–20, 1991.
[5] A. A. Abu-Dayya and N. C. Beaulieu, "Micro- and macrodiversity NCFSK (DPSK) on shadowed Nakagami-fading channels," *IEEE Trans. Commun.*, vol. 42, pp. 2693–2702, Sept. 1994.
[6] ——, "Micro- and macrodiversity {MDPSK} on shadowed frequency-selective channels," *IEEE Trans. Commun.*, vol. 43, pp. 2334–2343, Aug. 1995.
[7] L. C. Wang and C. T. Lea, "Performance gain of a S-macrodiversity in a lognormal shadowed Rayleigh Fading channel," *Electron. Lett.*, vol. 31, pp. 1785–1787, Sept. 1995.
[8] Y. H. Yeh, J. C. Wilson, and S. C. Schwartz, "Outage probability in mobile telephone with directive antennas and macrodiversity," *IEEE J. Select. Areas Commun.*, vol. 2, pp. 507–511, July 1984.
[9] R. C. Bernhardt, "Macroscopic diversity in frequency reuse radio systems," *IEEE J. Select. Areas Commun.*, vol. 3, pp. 862–870, June 1987.
[10] L. C. Wang and C. T. Lea, "Macrodiversity cochannel interference analysis," *Electron. Lett.*, vol. 31, pp. 614–616, Apr. 1995.
[11] A. M. D. Turkmani, "Probability of error for M-branch macroscopic selection diversity," *Proc. Inst. Elect. Eng.*, vol. 139, pt. I, pp. 71–78, Feb. 1992.
[12] J. P. M. G. Linnartz, "Site diversity in land mobile cellular telephony network with discontinuous voice transmission," *Europ. Trans. Telecommun.*, vol. 2, no. 5, pp. 471–480, 1991.
[13] G. L. Stüber and L. Yiin, "Downlink outage predictions for cellular radio systems," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 521–531, Aug. 1991.
[14] R. Prasad and A. Kegel, "Effects of Rician and lognormal shadowed signals on spectrum efficiency in microcellular radio," *IEEE Trans. Veh. Technol.*, vol. 42, pp. 274–281, Aug. 1993.
[15] A. A. Abu-Dayya and N. C. Beaulieu, "Outage probabilities of diversity cellular systems with cochannel interference in Nakagami fading," *IEEE Trans. Veh. Technol.*, vol. 41, no. 4, pp. 343–355, 1992.
[16] ——, "Outage probabilities in the presence of correlated lognormal interferers," *IEEE Trans. Veh. Technol.*, vol. 43, no. 1, pp. 164–173, 1994.

[17] A. Safak, "Optimal channel reuse in cellular radio systems with multiple correlated lognormal interferers," *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, pp. 304–312, 1994.
[18] P. Harley, "Short distance attenuation measurements at 900 MHz and 1.8 GHz using low antenna heights for microcells," *IEEE Select. Areas Commun.*, vol. 7, no. 1, pp. 5–11, 1989.
[19] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*. New York: McGraw-Hill, 1991.
[20] S. C. Schwartz and Y. S. Yeh, "On the distribution function and moments of power sums with lognormal components," *Bell Syst. Tech. J.*, vol. 61, pp. 1441–1462, Sept. 1982.
[21] L. C. Wang and C. T. Lea, "Incoherent estimation on co-channel interference probability for microcellular systems," to be published.
[22] W. B. Davenport, Jr. and W. L. Root, *An Introduction to the Theory of Random Signals and Noise*. New York: IEEE Press, 1987.
[23] M. Abramowitz and I. A. Stefun, *Handbook of Mathematical Functions*, 1965, p. 941.

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