Investigations into Cochannel Interference in Microcellular Mobile Radio Systems

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***Abstract*—A microcell interference model termed the Nakagami m_x/m_y is introduced in this paper. The desired signal as well as the cochannel interferers are assumed to have Nakagami statistics but with different amounts of fading. A special case of this model is obtained when the desired signal has Nakagami statistics while the cochannel interferers are subject to Rayleigh fading. The probability density function of the signal-to-interference ratio in the Nakagami m_x/m_y model is derived. This model is also compared with a Rician/Rayleigh microcellular model. The Nakagami m_x/m_y model is chosen to investigate the microcellular systems because Nakagami distributions fit experimental data better than either Rayleigh or Rician distributions in many cases. Expressions for the outage probabilities in microcell systems are derived. Numerical results show that, compared to medium/large cell systems, the microcellular systems have a lower outage probability. The impact of diversity on the microcellular system is also studied. Both signal-to-noise plus interference ratio selection diversity and signal-plus-interference selection diversity are investigated and an improvement to the outage probability due to diversity is observed.**

I. Introduction

In mobile ratio communications, frequency reuse is essential in increasing spectrum efficiency, and the application of this concept has resulted in the development of cellular radio systems. Integration of microcellular structure with the present medium/large cell system is considered to be vital to truly ubiquitous communications [1]–[3].

The presence of cochannel interference because of frequency reuse is seen to be a major problem in cellular radio systems regardless of cell size. Extensive studies of cochannel interference effects on medium/large cell radio systems have been made [4]–[13]. Several statistical models, Rayleigh [7], [10], [12], log-normal shadowing [4], [9], and superimposed Rayleigh fading and log-normal shadowing [5], [6], [8], [13], have been used to describe the environment. There is a common assumption in all these studies, however, that all signals received, desired and undesired, have the same statistical characteristics. For example, in [7], both the desired signal and undesired cochannel interferers are assumed to be subject to Rayleigh fading. Such an assumption is quite reasonable for medium to large cell systems. For microcellular systems, however, its validity is in question. For instance, in a microcellular environment, an undesired signal from a distant cochannel cell may well be modeled by Rayleigh statistics, but Rayleigh fading may not be a good assumption for the desired signal since a line-of-sight path may exist within a microcell [3], [14]. Therefore, in this situation, different fading statistics are needed to characterize the desired and undesired signals in a microcellular radio system.

The key point in microcell interference modeling is that the desired and undesired signals should have different statistical characteristics. One such interference model is introduced in [15]. The desired signal is assumed to have Rician statistics implying that a dominant multipath reflection exists in within-cell transmission. The interference signals from cochannel cells are assumed to be subject to Rayleigh fading because of the absence of a line-of-sight propagation. This model describes a Rician/Rayleigh fading environment [15]. Since mobile radio fading is usually studied using Rayleigh or Rician statistics, the Rician/Rayleigh model is introduced straightforwardly. However, a different (probably better) approach to study the cochannel interference is to use Nakagami distributions [16]–[18] for several reasons. First, the Nakagami distribution takes the Rayleigh distribution as a special case as does the Rician distribution, but it has a simpler probability density function expression. Second, the Nakagami distribution can approximate the Rician distribution and log-normal distribution very well [16], [19]. Third, Nakagami distributions can model fading conditions which are more or less severe than that of Rayleigh [20]. Finally and most importantly, Nakagami distributions fit experimental data better than Rayleigh, Rician or log-normal distributions in many cases [19], [21]. At the least, it is believed that the approach via Nakagami distributions is an alternative to that via Rayleigh or Rician distributions.

In this paper, we investigate the cochannel interference in microcellular mobile radio systems in which the signals have Nakagami characteristics. Similar to the Rician/Rayleigh model [15], in which desired and interfering signals have different fading characteristics, we assume that the desired as well as interfering signals have Nakagami characteristics but with different parameters, i.e., different amounts of fading, AF (AF is defined as the ratio of the variance of the received energy to the square of the mean of the received energy). This is termed a Nakagami m_x/m_y model, where m_x and m_y are related to the AF of desired and undesired signals, respectively. In a special case where the statistics of the undesired signals approach Rayleigh, we get a Nakagami/Rayleigh interference model.

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This paper is organized as follows. Section II presents the Nakagami m_x/m_y model. The probability density function of the power ratio between the desired and undesired signals is derived in this section, and a comparison between the Nakagami m_x/m_y model and the Rician/Rayleigh model is also made. In Section III, the outage probability, an important performance criterion of microcellular systems, is derived. The impact of diversity on the performance of microcellular radio systems is studied in Section IV. In particular, the outage probability improvement due to diversity is observed. Conclusions are presented in Section V.

II. Microcell Interference Model

A. Nakagami m_x/m_y Model

The AF of the desired signal is assumed to be $1/m_x$. The envelope, α, of the desired signal is a random variable with a Nakagami probability density function (pdf) [16], [19], i.e.,

$$p_\alpha(\alpha) = \frac{2}{\Gamma(m_x)}\left(\frac{m_x}{2X_m}\right)^{m_x}\alpha^{2m_x-1}\exp\left(-\frac{m_x}{2X_m}\alpha^2\right) \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, X_m is the mean signal power, and $m_x \geq 1/2$.

The signal power, x, measured over one RF cycle is $(1/2)\alpha^2$. The pdf of x is found to be

$$\begin{aligned} p_x(x) &= p_\alpha(\alpha)\frac{d\alpha}{dx} \\ &= \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x}x^{m_x-1}\exp\left(-\frac{m_x}{X_m}x\right) \quad (2)\end{aligned}$$

which is a gamma pdf [22]. Note that (1) and (2) degenerate into Rayleigh and exponential pdf, respectively, when $m_x = 1$. As m_x increases, AF decreases. The parameter m_x in Nakagami distributions can take any real value greater than or equal to 0.5. In this paper, however, we consider only integer values of $m_x\,(m_x = 1, 2, 3, \ldots)$.

Assume that there are I mutually independent Nakagami fading interferers, each with AF $1/m_y$ and mean power Y_m. The power of each interferer (measured over one RF cycle) is then a Gamma distributed random variable. The total interference power, y, is the sum of the I interference powers. Using Laplace transforms, the pdf of y is found to be [23]

$$p_y(y) = \left(\frac{m_y}{Y_m}\right)^{m_yI}\frac{y^{m_yI-1}}{\Gamma(m_yI)}\exp\left(-\frac{m_y}{Y_m}y\right). \quad (3)$$

Defining the signal-to-interference power ratio as $r = x/y$, we derive the pdf of r as follows:

$$\begin{aligned} p_r(r) &= \int_0^\infty y p_x(ry)p_y(y)dy \\ &= \frac{1}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI} \\ &\quad\times\int_0^\infty (ry)^{m_x-1}y^{m_yI}\exp\left[-\left(\frac{m_xr}{X_m}+\frac{m_y}{Y_m}\right)y\right]dy \\ &= \frac{\Gamma(m_x+m_yI)}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI} \\ &\quad\times r^{m_x-1}\left(\frac{m_xr}{X_m}+\frac{m_y}{Y_m}\right)^{-m_x-m_yI}. \quad (4)\end{aligned}$$

Letting $b_m = X_m/Y_m$, we get

$$\begin{aligned} p_r(r) =& \frac{\Gamma(m_x+m_yI)}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{b_m}\right)^{m_x} \\ &\times m_y^{m_yI}r^{m_x-1}\left(\frac{m_x}{b_m}r+m_y\right)^{-m_x-m_yI}. \quad (5)\end{aligned}$$

In the above analysis, (3) and (5) are valid only for the case where all cochannel interferers have the same mean power, Y_m. For the cases in which some interferers have different mean powers, different derivations are needed to obtain expressions of the pdf of total interference power and the pdf of signal-to-interference power ratio. For the special case where $m_y = 1$ (Rayleigh interference) and all interferers have mutually different mean powers, the pdf of y and that of r are obtained as follows.

Assume that the ith interferer $(1 \leq i \leq I)$ has mean power Y_{mi} and $Y_{mi} \neq Y_{mj}$ when $i \neq j$. Also, all interferers have AF $= 1$ implying that each interfering signal has Rayleigh statistics. Thus, the total interference power, y, is the sum of I independent exponentially distributed random variables. Following Renyi [23] and Sowerby and Williamson [24], the pdf of y is found to be

$$p_y(y) = \sum_{i=1}^{I}Y_{mi}^{I-2}\exp\left(-\frac{y}{Y_{mi}}\right)\prod_{j=1,\,j\neq i}^{I}\frac{1}{Y_{mi}-Y_{mj}}. \quad (6)$$

The pdf of the signal-to-interference power ratio is found as

$$\begin{aligned} p_r(r) =& \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x}\sum_{i=1}^{I}Y_{mi}^{I-2}\int_0^\infty y(ry)^{m_x-1} \\ &\cdot\exp\left[-\left(\frac{m_xr}{X_m}+\frac{1}{Y_{mi}}\right)y\right]dy\prod_{j=1,j\neq i}^{I}\frac{1}{Y_{mi}-Y_{mj}} \\ =& m_x\left(\frac{m_x}{X_m}\right)^{m_x}r^{m_x-1}\sum_{i=1}^{I}Y_{mi}^{I-2}\left(\frac{m_xr}{X_m}+\frac{1}{Y_{mi}}\right)^{-m_x-1} \\ &\cdot\prod_{j=1,\,j\neq i}^{I}\frac{1}{Y_{mi}-Y_{mj}} \\ =& m_x^{m_x+1}r^{m_x-1}\sum_{i=1}^{I}\frac{b_{mi}}{(m_xr+b_{mi})^{m_x+1}} \\ &\cdot\prod_{j=1,\,j\neq i}^{I}\frac{b_{mj}}{b_{mj}-b_{mi}} \quad (7)\end{aligned}$$

where $b_{mi} = X_m/Y_{mi}$.

The pdf curves of signal-to-interference power ratio are given in Figs. 1 and 2. In Fig. 1, the Nakagami m_x/m_y model with $m_y = 2$ is considered. Three cochannel interferers $(I = 3)$ each having equal mean power with $b_m = 5$ are assumed to be present. Fig. 1(a) shows the general tendency of the pdf while nine pdf curves are shown in Fig. 1(b) for various $m_x\,(m_x = 2, 3, 4, 5, 7, 9, 11, 13, 15)$. In Fig. 2, the Nakagami/Rayleigh model $(m_y = 1)$ with three cochannel interferers having mutually different mean powers $(b_{m1} =$

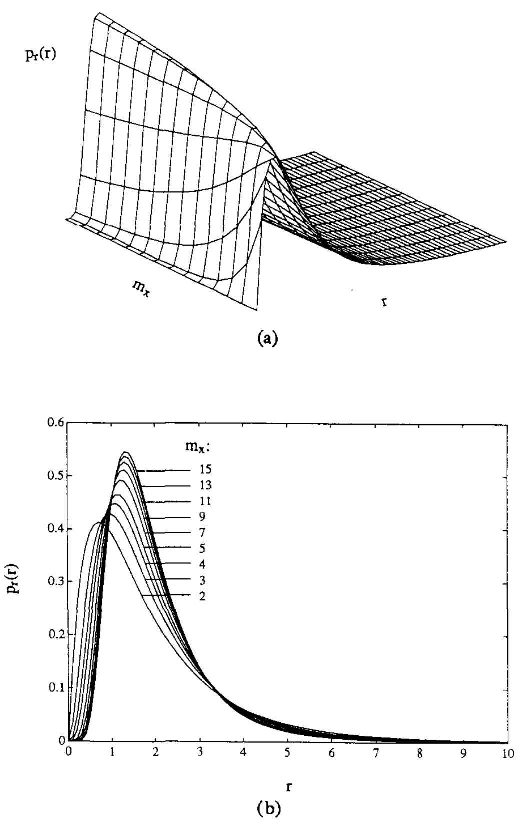

Fig. 1. The pdf of signal-to-interference power ratio; a Nakagami m_x/m_y model ($m_y = 2$) with equal mean interference power ($I = 3, b_m = 5$); (5).

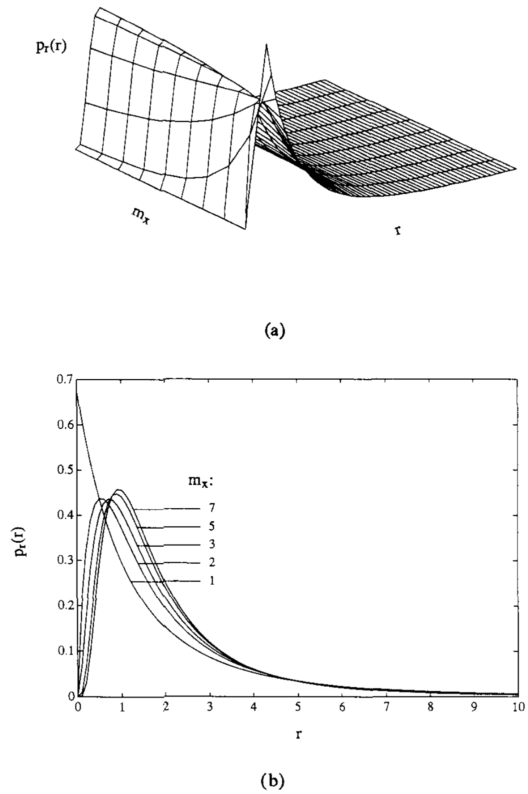

Fig. 2. The pdf of signal-to-interference power ratio; a Nakagami m_x/m_y model ($m_y = 1$, i.e., a Nakagami/Rayleigh model) with mutually different mean interference power ($I = 3, b_{m1} = 3, b_{m2} = 5, b_{m3} = 7$); (7).

$3, b_{m2} = 5$, and $b_{m3} = 7$) is considered. The general tendency of the pdf is shown in Fig. 2(a) and five curves are shown ($m_x = 1, 2, 3, 5, 7$) in Fig. 2(b). Notice that the curve for $m_x = 1$ is distinctly different from others.

Using the pdf of the signal-to-interference ratio in (5) or (7), it is easy to evaluate system performance in an interference-limited environment (i.e., noise is negligible and interference is the major concern) with Nakagami m_x/m_y or Nakagami/Rayleigh characteristics. For the case with only one interferer, the performance analysis can be found in [17] and [18]. In Section III, we study the system performance in the presence of multiple interferers. We first consider an interference-limited environment and then an environment limited by both noise and interference.

B. Comparison with Rician/Rayleigh Model

In the Rician/Rayleigh interference model, the envelope of the desired signal has Rician statistics with a pdf

$$p_\alpha(\alpha) = \frac{\alpha}{X}\exp\left(-\frac{\alpha^2+s^2}{2X}\right)I_0\left(\frac{\alpha s}{X}\right). \tag{8}$$

The pdf of the corresponding signal power is

$$p_x(x) = \frac{1}{X}\exp\left(-\frac{2x+s^2}{2X}\right)I_0\left(\frac{\sqrt{2x}s}{X}\right) \tag{9}$$

which is a noncentral chi-square pdf with two degrees of freedom [22]. In (8) and (9), $I_0(\cdot)$ is the modified Bessel function of the first kind and order zero. The mean signal power is $X + s^2/2$, where X is contributed by the diffused signal component and $s^2/2$ by the direct line-of-sight signal component.

Fading signals are studied using either their envelope statistics or signal power statistics. It is well known that a Rayleigh fading signal has a signal power with an exponential distribution. For a Rician fading signal, the signal power is distributed following a noncentral chi-square pdf with two degrees of freedom as shown in (9). In the case of Nakagami fading, a Gamma distribution characterizes the signal power. The relation between fading signal envelope and signal power in three fading environments (Rayleigh, Rician and Nakagami) are listed in Table I for comparison. Interrelations between several other forms of statistical distributions are found in [25].

The cochannel interferers in the Rician/Rayleigh model are subject to Rayleigh fading. The pdf of the total interference power of I interferers is obtained using (3), with $m_y = 1$ and the mean power of each interferer Y. The pdf of the signal-to-interference power ratio is thus obtained as

$$p_r(r) = \int_0^\infty \frac{y}{X}\exp\left(-\frac{2ry+s^2}{2X}\right)I_0\left(\frac{\sqrt{2ry}s}{X}\right)$$

TABLE I
RELATIONSHIP BETWEEN FADING SIGNAL ENVELOPE AND THE SIGNAL POWER

Fading Statistics	Envelope pdf	Signal Power pdf	Comments
Rayleigh fading	Rayleigh	exponential	a special case of Rician and Nakagami fading
Rician fading	Rician	noncentral chi-square with two degrees of freedom	degenerating into Rayleigh fading when $s = 0$
Nakagami fading	Nakagami	Gamma	degenerating into Rayleigh fading when $m_x = 1$

$$\times \frac{y^{I-1}}{Y^I(I-1)!}\exp\left(-\frac{y}{Y}\right)dy$$
$$= \frac{I}{b}\left(\frac{b}{r+b}\right)^{I+1}\exp\left(-\frac{ab}{r+b}\right)\sum_{i=0}^{I}C_I^{I-i}\frac{1}{i!}\left(\frac{ar}{r+b}\right)^i \tag{10}$$

where $a = s^2/2X$, $b = X/Y$ and C_I^{I-i} is a binomial coefficient, i.e., $I!/i!(I-i)!$. The pdf given in (10) is valid for the case where all Rayleigh interferers have the same mean power. If all interferers have mutually different mean powers (i.e., the ith interferer $(1 \le i \le I)$ has mean power Y_i and $Y_i \ne Y_j$ when $i \ne j$), the pdf of the total interference power is obtained using (6) and the pdf of the signal-to-interference power ratio is found to be

$$p_r(r) = \int_0^\infty \frac{y}{X}\exp\left(-\frac{2ry+s^2}{2X}\right)I_0\left(\frac{\sqrt{2rys}}{X}\right) \cdot \sum_{i=1}^{I}Y_i^{I-2}\exp\left(-\frac{y}{Y_i}\right)\prod_{j=1,\,j\ne i}^{I}\frac{1}{Y_i-Y_j}dy$$
$$= \sum_{i=1}^{I}\frac{b_i}{(r+b_i)^2}\left(1+\frac{ar}{r+b_i}\right)\exp\left(-\frac{ab_i}{r+b_i}\right) \cdot \prod_{j=1,\,j\ne i}^{I}\frac{b_j}{b_j-b_i} \tag{11}$$

where $b_i = X/Y_i$.

If a single interferer is considered, the pdf of the signal-to-interference ratio when both signal and interferer have Rician statistics (i.e., Rician/Rician fading, a more general case of Rician/Rayleigh fading) can be found in [26].

Fig. 3(a) shows the pdf of the signal-to-interference power ratio, (10), in a Rician/Rayleigh environment, in which $a = 0.25$ or 4 is assumed while keeping $(a+1)b$, i.e., $(s^2/2 + X)/Y$, constant. In Figs. 3(b)–3(d), the pdf of the signal-to-interference power ratio using the Nakagami m_x/m_y model given by (5) are plotted for different values of m_y and m_x. Comparing the two models, Rician/Rayleigh and Nakagami m_x/m_y, it is observed that the former can be approximated

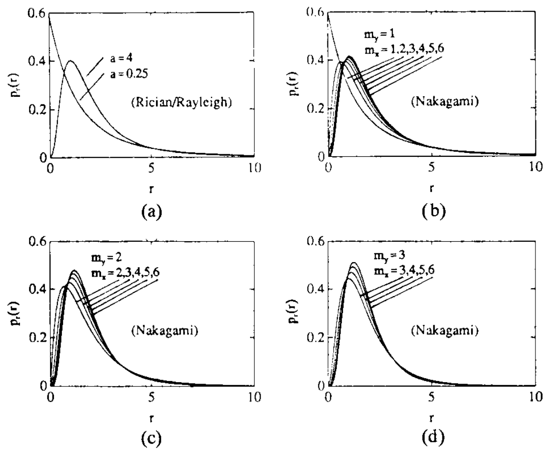

Fig. 3. The pdf of signal-to-interference power ratio; a comparison of Rician/Rayleigh and Nakagami m_x/m_y models ($I = 3$, $(a+1)\,b = b_m = 5$); (10) and (5).

by the latter. It is also known that Nakagami distributions lead to greater flexibility in matching experimental data than Rayleigh or Rician distributions [19]. We believe, therefore, that the Nakagami m_x/m_y model is more appropriate than the Rician/Rayleigh for investigating cochannel interference in microcellular radio environments. In the following, we study the performance of microcellular systems using the Nakagami m_x/m_y model. In particular, expressions for system outage probabilities are derived.

III. OUTAGE PROBABILITIES IN MICROCELL SYSTEMS

In cellular radio systems, adequate signal strength and signal-to-interference ratio are essential for successful communications. Therefore, the outage probability defined as the probability of failing to achieve simultaneously a signal-to-noise ratio and a signal-to-interference ratio sufficient to give satisfactory reception is an appropriate measure to evaluate the performance of a cellular radio system [6]–[8]. A simpler analysis may need only one of the two requirements, either signal-to-noise ratio [27] or signal-to-interference ratio [5], for system evaluation. For example, in an interference-limited environment, we need to consider only the signal-to-interference ratio requirement.

A. Interference-Limited Environment

Assuming that the signal-to-interference protection ratio is R_I, the outage probability is simply

$$P_{\text{out}} = \Pr(r < R_I) = \int_0^{R_I} p_r(r)dr \tag{12}$$

where $p_r(r)$ is the pdf of the signal-to-interference ratio. Considering the Nakagami m_x/m_y model with equal mean interference powers, we use (5) into (12) and get

$$P_{\text{out}} = \frac{\Gamma(m_x+m_yI)}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{b_m}\right)^{m_x} m_y^{m_yI}\int_0^{R_I} r^{m_x-1}$$

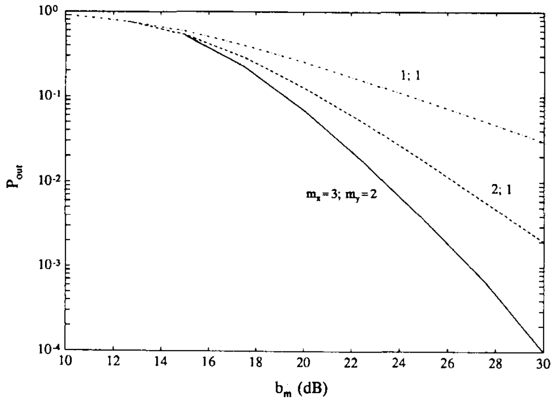

Fig. 4. The outage probability ($I = 6, R_I = 5$); (13).

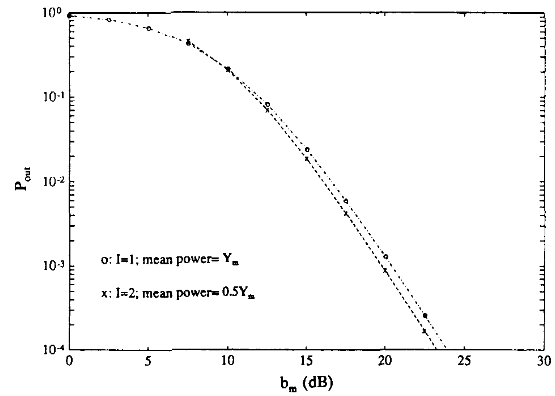

Fig. 5. The outage probability; a comparison of one- and two-interferer cases $m_x = 3, m_y = 2, R_I = 5$); (13).

$$\cdot \left(\frac{m_x}{b_m} r + m_y\right)^{-m_x - m_y I} dr$$
$$= \frac{\Gamma(m_x + m_y I)}{\Gamma(m_x)\Gamma(m_y I)} \left(\frac{m_x}{b_m}\right)^{m_x} m_y^{m_y I} m_y^{-m_x - m_y I} \frac{R_I^{m_x}}{m_x}$$
$$\cdot F\left(m_x + m_y I, m_x; 1 + m_x; -\frac{m_x}{m_y b_m} R_I\right)$$
$$= \frac{\Gamma(m_x + m_y I)}{m_x \Gamma(m_x)\Gamma(m_y I)} \left(\frac{m_x R_I}{m_y b_m}\right)^{m_x}$$
$$\cdot F\left(m_x + m_y I, m_x; 1 + m_x; -\frac{m_x}{m_y b_m} R_I\right) \quad (13)$$

where $F(\cdot, \cdot; \cdot; \cdot)$ is the hypergeometric series [28] defined as

$$F(\alpha, \beta; \gamma; z) = \frac{\Gamma(\gamma)}{\Gamma(\alpha)\Gamma(\beta)} \sum_{n=0}^{\infty} \frac{\Gamma(\alpha + n)\Gamma(\beta + n)}{\Gamma(\gamma + n)} \cdot \frac{z^n}{n!}. \quad (14)$$

Similarly, for the case $m_y = 1$ and all interferers have mutually different mean powers, using (7) and (12), the outage probability is found as

$$P_{\text{out}} = (m_x R_I)^{m_x} \sum_{i=1}^{I} b_{mi}^{-m_x}$$
$$\times F\left(m_x + 1, m_x; m_x + 1; -\frac{m_x}{b_{mi}} R_I\right)$$
$$\times \prod_{j=1, j \neq i}^{I} \frac{b_{mj}}{b_{mj} - b_{mi}}. \quad (15)$$

If only one Nakagami interferer is considered, the outage probability expression is obtained in a form of an incomplete beta function [17].

The outage probabilities given in (13) are plotted in Fig. 4 for different values of m_x and m_y. The case, $m_x = m_y = 1$, is actually a Rayleigh/Rayleigh model characterizing medium/large cell systems. It is observed that much lower outage probabilities are achieved in microcell systems (Nakagami m_x/m_y model) compared with medium/large cell systems (Rayleigh/Rayleigh model).

Fig. 5 compares two cases, both with the Nakagami m_x/m_y model. In one case, there is one interferer with mean power Y_m, while in the other, there are two interferers with total mean power Y_m (each with $0.5Y_m$). It is interesting to see that they gave approximately the same result.

B. Consideration of Both Noise and Interference

Considering both the signal-to-noise ratio requirement (assuming that the minimum required desired signal power is $R_N X_m$) and the signal-to-interference ratio requirement (assuming that the signal-to-interference protection ratio is R_I), the outage probability is [15]

$$P_{\text{out}} = 1 - \Pr(x > R_N X_m, \, x/y > R_I)$$
$$= 1 - \int_{R_N X_m}^{\infty} \left[\int_0^{x/R_I} p_y(y) dy\right] p_x(x) dx \quad (16)$$

where $p_x(x)$ is the pdf of the signal power as given in (2) and $p_y(y)$ is the pdf of the interference power shown in (3) (the equal mean power case). We have

$$\int_0^{x/R_I} p_y(y) dy$$
$$= \left(\frac{m_y}{Y_m}\right)^{m_y I} \frac{1}{\Gamma(m_y I)}$$
$$\cdot \int_0^{x/R_I} y^{m_y I - 1} \exp\left(-\frac{m_y}{Y_m} y\right) dy$$
$$= \left(\frac{m_y}{Y_m}\right)^{m_y I} \frac{1}{\Gamma(m_y I)} \left[\frac{(m_y I - 1)!}{(m_y / Y_m)^{m_y I}}\right.$$
$$- \exp\left(-\frac{x}{R_I} \cdot \frac{m_y}{Y_m}\right)$$
$$\left.\cdot \sum_{k=0}^{m_y I - 1} \frac{(m_y I - 1)!}{k!} \frac{(x/R_I)^k}{(m_y / Y_m)^{m_y I - k}}\right]$$
$$= 1 - \exp\left(-\frac{m_y}{Y_m} \cdot \frac{x}{R_I}\right) \sum_{k=0}^{m_y I - 1} \frac{1}{k!} \left(\frac{m_y}{Y_m} \cdot \frac{x}{R_I}\right)^k. \quad (17)$$

Note that the integration in (17) is an incomplete gamma function [28].

Using (17) in (16), we get

$$\begin{aligned} P_{\text{out}} = 1 - &\frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x} \\ &\cdot \int_{R_N X_m}^{\infty} x^{m_x - 1}\exp\left(-\frac{m_x}{X_m}x\right)dx \\ &+ \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x}\int_{R_N X_m}^{\infty} \\ &\cdot \exp\left(-\frac{m_y}{Y_m}\cdot\frac{x}{R_I}\right)\sum_{k=0}^{m_y I - 1}\frac{1}{k!}\left(\frac{m_y}{Y_m}\cdot\frac{x}{R_I}\right)^k \\ &\cdot x^{m_x-1}\exp\left(-\frac{m_x}{X_m}x\right)dx \\ = 1 - &\exp(-R_N m_x)\sum_{k=0}^{m_x-1}\frac{(R_N m_x)^k}{k!} \\ &+ \frac{m_x^{m_x}}{\Gamma(m_x)}\exp\left[-R_N\left(\frac{m_y b_m}{R_I} + m_x\right)\right] \\ &\times \sum_{k=0}^{m_y I-1}\frac{1}{k!}\left(\frac{m_y b_m}{R_I}\right)^k\sum_{j=0}^{k+m_x-1}\frac{(k+m_x-1)!}{j!} \\ &\cdot \frac{R_N^j}{(m_y b_m/R_I + m_x)^{k+m_x-j}}. \end{aligned} \tag{18}$$

Equation (18) produces the same result as (13) when $R_N = 0$, i.e., only the signal-to-interference ratio requirement is considered. If the noise is a major concern while the interference is absent, the outage probability is obtained by assuming $R_I = 0$ in (18),

$$P_{\text{out}} = 1 - \exp(-R_N m_x)\sum_{k=0}^{m_x-1}\frac{(R_N m_x)^k}{k!}. \tag{19}$$

Equations (17)–(19) give the results when the interferers have the same mean power. If all interferers have mutually different mean powers, using (2), (6), and (16), we can find

$$\begin{aligned} \int_0^{x/R_I} p_y(y)dy = &\sum_{i=1}^{I}\sum_{j=1,\, j\neq i}^{I}\frac{Y_{mi}}{Y_{mi}-Y_{mj}} \\ &- \sum_{i=1}^{I}\exp\left(-\frac{x}{Y_{mi}R_I}\right) \\ &\times \prod_{j=1,\, j\neq i}^{I} c\frac{Y_{mi}}{Y_{mi}-Y_{mj}} \end{aligned} \tag{20}$$

and

$$\begin{aligned} P_{\text{out}} = 1 - &\left(\sum_{i=1}^{I}\prod_{j=1, j\neq i}^{I}\frac{Y_{mi}}{Y_{mi}-Y_{mj}}\right) \\ &\cdot \exp(-R_N m_x)\sum_{k=0}^{m_x-1}\frac{(R_N m_x)^k}{k!} \\ &+ \frac{1}{\Gamma(m_x)}\sum_{i=1}^{I}\left(\frac{b_{mi}}{R_I m_x}+1\right)^{-1} \\ &\cdot \exp\left[-\left(\frac{b_{mi}R_N}{R_I} + m_x R_N\right)\right] \\ &\times \sum_{k=0}^{m_x-1}\left(\frac{b_{mi}R_N}{R_I} + m_x R_N\right)^k\frac{(m_x-1)!}{k!} \\ &\cdot \prod_{j=1,\, j\neq i}^{I}\frac{Y_{mi}}{Y_{mi}-Y_{mj}}. \end{aligned} \tag{21}$$

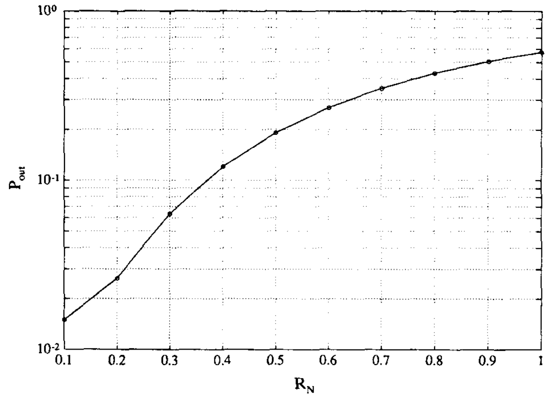

Fig. 6. The outage probability; considering both signal-to-noise ratio and signal-to-interference ratio requirements ($m_x = 3, m_y = 2, I = 3, R_I = 5, b_m = 20$ dB); (18).

Using (18), Fig. 6 shows the system outage probability when requirements on both signal-to-noise ratio and signal-to-interference ratio are imposed. In the figure, $m_x = 3$, $m_y = 2$, $I = 3$, $R_I = 5$, and $b_m = 20$ dB are assumed.

IV. Cochannel Interference Suppression Using Diversity

Diversity is widely used to combat deep fading in mobile radio environments [29]. This technique is also used in cellular systems to suppress cochannel interference [24], [30], [31]. The simplest approach is to use selection diversity where the antenna with the highest signal-to-noise plus interference ratio is connected to the output.

A. Signal-Plus-Interference Selection Diversity

Ideally, the branch with the largest instantaneous signal-to-noise plus interference ratio should be selected in order to achieve the best selection diversity performance. However, it is very difficult to continuously measure the signal-to-noise plus interference ratio of each individual branch [24]. A more realistic option would be to select the branch with the strongest total signal [24], [31], i.e., desired signal plus interferers. For simplicity, an interference-limited system is assumed in this subsection.

Using the signal-plus-interference selection diversity (M branches), following Schiff [31] and Sowerby and Williamson [24], the outage probability is

$$\begin{aligned} P_{\text{out}}^{(M)} = 1 - M\Pr\Big\{&\frac{x^{\langle b1\rangle}}{y^{\langle b1\rangle}} \geq R_I, x^{\langle b1\rangle} + y^{\langle b1\rangle} \\ &> x^{\langle bi\rangle} + y^{\langle bi\rangle}, \qquad \text{for } i = 2, 3, \cdots, M\Big\} \end{aligned}$$

$$= 1 - M \int_{R_I}^{\infty} \int_0^{\infty} p_{uv}(u, v)[\Pr(x + y < v)]^{M-1} dv du \tag{22}$$

where $\langle bi \rangle$ indicates branch $i, u = x/y, v = x + y$, and $p_{uv}(u, v)$ is the joint pdf of u and v,

$$\begin{aligned} p_{uv}(u, v) &= \frac{v}{(u+1)^2} p_x(x) p_y(y) \\ &= \frac{1}{\Gamma(m_x)\Gamma(m_y I)} \left(\frac{m_x}{X_m}\right)^{m_x} \left(\frac{m_y}{Y_m}\right)^{m_y I} \frac{u^{m_x - 1}}{(u+1)^{m_x + m_y I}} \\ &\times v^{m_x + m_y I - 1} \exp\left[-\left(\frac{m_x}{X_m} u + \frac{m_y}{Y_m}\right) \frac{v}{u+1}\right]. \end{aligned} \tag{23}$$

The probability of $x + y$ being smaller than v is derived in Appendix I and given in (29). Inserting (23) and (29) into (22), the outage probability is obtained in a form of a double integral, which can be numerically evaluated. For a case of dual selection diversity ($M = 2$), the expression of the outage probability is simplified as

$$P_{\text{out}}^{(2)} = 1 - 2 \int_{R_I}^{\infty} \int_0^{\infty} p_{uv}(u, v) \Pr(x + y < v) dv du. \tag{24}$$

In (24), the integration over v is expressed in four terms as derived in Appendix II ((30)–(33)).

Using (30)–(33) in (24), the outage probability of the system with signal-plus-interference selection diversity is evaluated using a single integral (over u from R_I to ∞).

Although the ideal signal-to-noise plus interference radio selection diversity is very difficult to implement, its performance analysis is considerably simpler compared to the analysis of signal-plus-interference selection diversity. Thus an illustration of the improvement in reception reliability offered by selection diversity is easily obtained by considering ideal selection diversity [32].

B. Signal-to-Noise Plus Interference Ratio Selection Diversity

In an ideal M-branch selection diversity scheme, the best branch (i.e., the branch with highest signal-to-noise plus interference ratio) is chosen. The system fails to achieve the required signal-to-noise and signal-to-interference ratios when and only when all branches fail to do so. Therefore, the outage probability when ideal selection diversity is used is simply

$$P_{\text{out}}^{(M)} = P_{\text{out}}^M \tag{25}$$

provided that all branches are mutually independent and have identical fading and interference characteristics. The improvement in outage probability due to ideal diversity is shown in Fig. 7, where two- and three-branch cases are compared with the case without diversity.

It has already been shown in Section II that the signal-to-interference ratio in a Nakagami m_x/m_y environment is characterized by a pdf given by (5). It is of interest to obtain the pdf of the signal-to-interference ratio when ideal selection diversity is used. As indicated in (12), the outage probability is essentially the cumulative distribution function of the signal-to-interference ratio. The pdf of the signal-to-interference ratio when selection diversity is employed is therefore obtained by differentiating (25). This results in

$$\begin{aligned} p_r^{(M)}(r) = & M\left[\frac{\Gamma(m_x + m_y I)}{\Gamma(m_x)\Gamma(m_y I)} \left(\frac{m_x}{b_m}\right)^{m_x} m_y^{m_y I}\right]^M \\ & \cdot r^{m_x - 1} \left(\frac{m_x}{b_m} r + m_y\right)^{-m_x - m_y I} \\ & \times \left[m_y^{-m_x - m_y I} \frac{r^{m_x}}{m_x}\right. \\ & \left.\cdot F\left(m_x + m_y I, m_x; 1 + m_x; -\frac{m_x}{m_y b_m} r\right)\right]^{M-1}. \end{aligned} \tag{26}$$

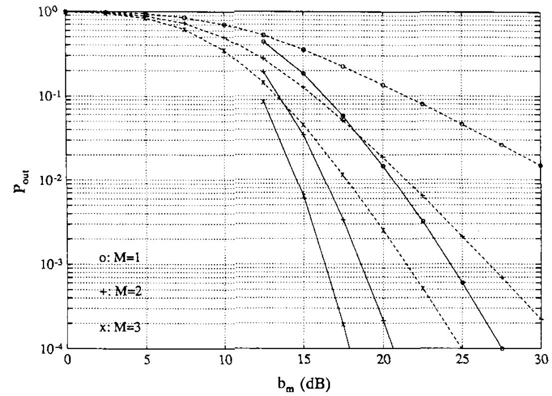

Fig. 7. Diversity effects on the outage probability ($I = 3, R_I = 5, R_N = 0$; dashed: $m_x = 1, m_y = 1$; solid: $m_x = 3, m_y = 2$); (13) and (25).

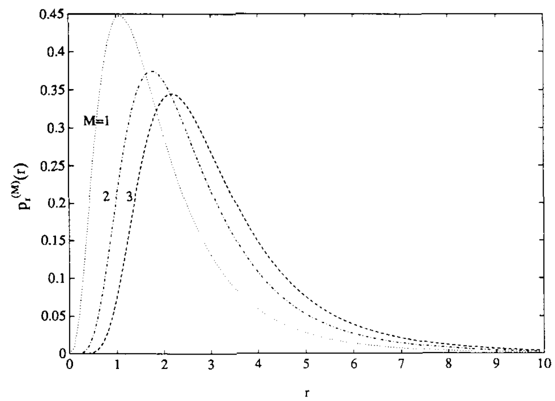

Fig. 8. Diversity effects on the pdf of signal-to-interference power ratio; a Nakagami m_x/m_y model ($m_x = 4, m_y = 2$) with equal mean interference power ($I = 3, b_m = 5$); (26).

The pdf curves of the cases with two- and three-branch diversity and no diversity are drawn in Fig. 8 which shows that the signal-to-interference ratio has a better chance to be high with the application of diversity.

V. Conclusion

The cochannel interference in microcellular systems has been investigated in this paper. An interference model named

Nakagami m_x/m_y was introduced. The desired signal as well as cochannel interferers are assumed to be subject to Nakagami fading, but the cochannel interferers experience deeper fading ($m_y < m_x$), which characterizes the microcellular environments. The pdf of the signal-to-interference ratio and the system outage probability are derived. Numerical results show that a lower outage probability is achieved in microcellular systems compared with medium/large cell systems in which the desired signal and interferers usually experience the same amount of fading. The diversity effect on the microcellular system has also been studied. Both ideal signal-to-noise plus interference ratio selection diversity and practical signal-plus-interference selection diversity are considered and an improvement of the outage probability due to diversity is observed.

Appendix I

In (22), the probability of $x + y$ being smaller than v is derived as follows:

$$\Pr\{x+y<v\} = \Pr\{y<v-x\} = \int_0^v \left[\int_0^{v-x} p_y(y)dy\right] p_x(x)dx. \quad (27)$$

Following (17), the integration over y in (27) is found as

$$\begin{aligned}\int_0^{v-x} p_y(y)dy &= 1 - \exp\left[-\frac{m_y}{Y_m}(v-x)\right] \cdot \sum_{k=0}^{m_yI-1} \frac{1}{k!}\left[\frac{m_y}{Y_m}(v-x)\right]^k \\ &= 1 - \exp\left(-\frac{m_y}{Y_m}v\right) \sum_{k=0}^{m_yI-1} \frac{1}{k!}\left(\frac{m_y}{Y_m}\right) \cdot \sum_{i=0}^{k} C_k^i v^{k-i}(-x)^i \exp\left(\frac{m_y}{Y_m}x\right). \quad (28)\end{aligned}$$

Then we have

$$\begin{aligned}&\Pr\{x+y<v\} \\ &= \int_0^v \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x} x^{m_x-1}\exp\left(-\frac{m_x}{X_m}x\right)dx \\ &\quad - \int_0^v \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x} \exp\left(-\frac{m_y}{Y_m}v\right)\sum_{k=0}^{m_yI-1}\frac{1}{k!}\left(\frac{m_y}{Y_m}\right) \\ &\quad \times \sum_{i=0}^{k} C_k^i v^{k-i}(-1)^i x^{i+m_x-1}\exp\left[-\left(\frac{m_x}{X_m}-\frac{m_y}{Y_m}\right)x\right]dx \\ &= 1 - \exp\left(-\frac{m_x}{X_m}v\right)\sum_{n=0}^{m_x-1}\frac{1}{n!}\left(\frac{m_x}{X_m}v\right)^n \\ &\quad - \frac{1}{\Gamma(m_x)}\left(\frac{m_x}{X_m}\right)^{m_x}\exp\left(-\frac{m_y}{Y_m}v\right)\sum_{k=0}^{m_yI-1}\frac{1}{k!}\left(\frac{m_y}{Y_m}\right) \\ &\quad \times \sum_{i=0}^{k} C_k^i v^{k-i}(-1)^i \left\{\frac{(i+m_x-1)!}{\left(\frac{m_x}{X_m}-\frac{m_y}{Y_m}\right)^{i+m_x}} - \exp\left[-\left(\frac{m_x}{X_m}-\frac{m_y}{Y_m}\right)v\right] \right. \\ &\quad \left. \times \sum_{n=0}^{i+m_x-1}\frac{(i+m_x-1)!}{n!}\cdot\frac{v^n}{\left(\frac{m_x}{X_m}-\frac{m_y}{Y_m}\right)^{i+m_x-n}}\right\}. \quad (29)\end{aligned}$$

Appendix II

In (24), the integration over v is expressed in four terms. The first term is

$$\begin{aligned}&\frac{1}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI}\frac{u^{m_x-1}}{(u+1)^{m_x+m_yI}} \\ &\quad \times \int_0^\infty v^{m_x+m_yI-1}\exp\left[-\left(\frac{m_x}{X_m}u+\frac{m_y}{Y_m}\right)\frac{v}{u+1}\right]dv \\ &= \frac{\Gamma(m_x+m_yI)}{\Gamma(m_x)\Gamma(m_yI)} m_x^{m_x} m_y^{m_yI} b_m^{m_yI}\frac{u^{m_x-1}}{(m_xu+b_mm_y)^{m_x+m_yI}}. \quad (30)\end{aligned}$$

The second term is

$$\begin{aligned}&-\frac{1}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI}\frac{u^{m_x-1}}{(u+1)^{m_x+m_yI}} \\ &\quad \times \sum_{n=0}^{m_x-1}\frac{(m_x/X_m)^n}{n!}\int_0^\infty v^{m_x+m_yI-1+n} \\ &\quad \cdot \exp\left\{-\left[\left(\frac{m_x}{X_m}u+\frac{m_y}{Y_m}\right)\frac{1}{u+1}+\frac{m_x}{X_m}\right]v\right\}dv \\ &= -\frac{1}{\Gamma(m_x)\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI} \\ &\quad \cdot \frac{u^{m_x-1}}{(u+1)^{m_x+m_yI}}\sum_{n=0}^{m_x-1}\frac{(m_x/X_m)^n}{n!} \\ &\quad \times (m_x+m_yI+n-1)! \\ &\quad \left[\left(\frac{m_x}{X_m}u+\frac{m_y}{Y_m}\right)\frac{1}{u+1}+\frac{m_x}{X_m}\right]^{-m_x-m_yI-n}. \quad (31)\end{aligned}$$

The third term is

$$-\frac{1}{[\Gamma(m_x)]^2\Gamma(m_yI)}\left(\frac{m_x}{X_m}\right)^{2m_x}\left(\frac{m_y}{Y_m}\right)^{m_yI+1}\frac{u^{m_x-1}}{(u+1)^{m_x+m_yI}}$$

$$\times \sum_{k=0}^{m_y I-1} \frac{1}{k!} \sum_{i=0}^{k} C_k^i (-1)^i$$

$$\cdot (i+m_x-1)! \left(\frac{m_x}{X_m} - \frac{m_y}{Y_m}\right)^{-i-m_x}$$

$$\times \int_0^\infty v^{m_x+m_y I-1+k-i}$$

$$\cdot \exp\left\{-\left[\left(\frac{m_x}{X_m}u + \frac{m_y}{Y_m}\right)\frac{1}{u+1} + \frac{m_y}{Y_m}\right]v\right\}dv$$

$$= -\frac{1}{[\Gamma(m_x)]^2\Gamma(m_y I)}\left(\frac{m_x}{X_m}\right)^{2m_x}$$

$$\cdot \left(\frac{m_y}{Y_m}\right)^{m_y I+1} \frac{u^{m_x-1}}{(u+1)^{m_x+m_y I}}$$

$$\times \sum_{k=0}^{m_y I-1} \frac{1}{k!} \sum_{i=0}^{k} C_k^i (-1)^i (i+m_x-1)!$$

$$\cdot \left(\frac{m_x}{X_m} - \frac{m_y}{Y_m}\right)^{-i-m_x}$$

$$\times (m_x + m_y I - 1 + k - i)!$$

$$\cdot \left[\left(\frac{m_x}{X_m}u + \frac{m_y}{Y_m}\right)\frac{1}{u+1} + \frac{m_y}{Y_m}\right]^{-m_x-m_y I-k+i}. \quad (32)$$

The fourth term is

$$\frac{1}{[\Gamma(m_x)]^2\Gamma(m_y I)}\left(\frac{m_x}{X_m}\right)^{2m_x}\left(\frac{m_y}{Y_m}\right)^{m_y I+1} \frac{u^{m_x-1}}{(u+1)^{m_x+m_y I}}$$

$$\times \sum_{k=0}^{m_y I-1} \frac{1}{k!} \sum_{i=0}^{k} C_k^i (-1)^i$$

$$\cdot \sum_{n=0}^{i+m_x-1} \frac{(i+m_x-1)!}{n!}\left(\frac{m_x}{X_m} - \frac{m_y}{Y_m}\right)^{-i-m_x+n}$$

$$\times \int_0^\infty v^{m_x+m_y I-1+k-i+n}$$

$$\cdot \exp\left\{-\left[\left(\frac{m_x}{X_m}u + \frac{m_y}{Y_m}\right)\frac{1}{u+1} + \frac{m_x}{X_m}\right]v\right\}dv$$

$$= -\frac{1}{[\Gamma(m_x)]^2\Gamma(m_y I)}\left(\frac{m_x}{X_m}\right)^{2m_x}$$

$$\cdot \left(\frac{m_y}{Y_m}\right)^{m_y I+1} \frac{u^{m_x-1}}{(u+1)^{m_x+m_y I}}$$

$$\times \sum_{k=0}^{m_y I-1} \frac{1}{k!} \sum_{i=0}^{k} C_k^i (-1)^i$$

$$\cdot \sum_{n=0}^{i+m_x-1} \frac{(i+m_x-1)!}{n!}\left(\frac{m_x}{X_m} - \frac{m_y}{Y_m}\right)^{-i-m_x+n}$$

$$\times (m_x + m_y I - 1 + k - i + n)!$$

$$\cdot \left[\left(\frac{m_x}{X_m}u + \frac{m_Y}{Y_m}\right)\frac{1}{u+1} + \frac{m_x}{X_m}\right]^{-m_x-m_y I-k+i-n}. \quad (33)$$

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