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Effect of Power Control Imperfections on the Reverse Link of Cellular CDMA Networks Under Multipath Fading

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***Abstract*—In this paper, we present an analytical approach for the evaluation of the impact of power control errors on the reverse link of a multicell direct sequence code-division multiple access (CDMA) system with fast power control under multipath fading. Unlike many previous papers, the joint effect of multipath fading and fast power control on interference statistics is explicitly accounted for and mobiles are assumed to connect to a base station according to a minimum attenuation criterion. Both the average bit error rate (BER) and the outage probabilities that a user experiences are estimated. The results have been used to evaluate the system capacity from two points of view. First, the maximum capacity supported by the system in order to maintain an average BER below a prescribed level has been calculated. Second, the maximum capacity possible to ensure that the outage probability does not exceed a set limit is analyzed. Capacity is shown to be significantly affected by the imperfections of power control. Our results can be used to quantify the relative capacity loss due to fast power control errors in a cellular CDMA network affected by slow fading, multipath fading, and cochannel interference.**

***Index Terms*—Cellular systems, code-division multiple access (CDMA), imperfect power control, interference statistics.**

I. Introduction

THIRD-GENERATION wireless communication systems must be able to provide a variety of new services with different requirements in quality under different traffic conditions. These systems are mostly based on the code-division multiple-access (CDMA) technique, which effectively uses the radio spectra by means of universal frequency reuse. Therefore, interference levels limit the capacity of such systems and, consequently, power control is required to achieve good performance [1]. Moreover, if fast power control is employed (as defined, for example in the third generation mobile radio systems standard UMTS), the rapid variations of the radio channel due to multipath fading can be compensated, at least in part, for users moving at a low or even moderate speed.

The analysis at a system level of multicell CDMA networks under multipath fading and fast power control has been mainly carried out through simulation due to the analytical complexity [2], [3]. Analytical results for the performance of multicell CDMA networks with perfect fast power control under multipath fading have been presented recently but, to simplify the analysis, it is usually assumed that users connect to the nearest base station [4]–[6]. However, in a real system, mobiles will connect to the base station that offers the best average propagation conditions [7]. A more realistic theoretical approach for the analysis of multicell CDMA networks with best base station assignment and ideal fast power control is presented in [8] and [9]. However, when applying power control in practice the performance is restricted by a number of limitations and therefore, perfect power control cannot be achieved [10]. Thus, the main aim in these systems is to maintain power level variations at a low enough level to avoid drastic reductions in system capacity and, therefore, the effect on system performance of imperfections in power control must be considered.

The issue of the effect of power control errors on CDMA systems has received a great deal of attention over the last few years [10]–[15]. Many of the previous papers analyzing the effects of power control imperfections on cellular CDMA networks do not explicitly address the effect of multipath fading, and its effect is included in the ratio of required energy per bit to interference density or in power control errors. Such simplification prevents an accurate characterization of the interference statistics, which are closely related to capacity in CDMA systems. Furthermore, intracell interference statistics are usually oversimplified in the analysis of multicell CDMA systems and render the results obtained inaccurate. In [12], the effect of power control imperfections is evaluated for a packet CDMA system. Though the interference statistics are accurately calculated by numerical analysis, only one isolated cell is considered. The impact of power control imperfections on a multicell CDMA system is examined in [13], but average intercell interference is accounted for by considering that it is a fraction of average intracell interference, while we have shown in [16] and [17] that this simplification leads to very optimistic results. An analysis explicitly considering the interference due to other-cell users can be found in [14] for a system in which shadowing is not considered and users connect to the nearest base station. In [15], a detailed analysis is performed for a system in which users connect to a given base station on a minimum attenuation basis and shadowing is considered for the calculation of intercell interference, but its effect is omitted for the derivation of the intracell interference statistics. Moreover, a theoretical approach to analyze the effect of multipath fading on interference statistics and its interaction with imperfect fast power control is not addressed in any of the mentioned papers.

The goal of this contribution is to derive an analytical model enabling a complete characterization of the effect of power con-

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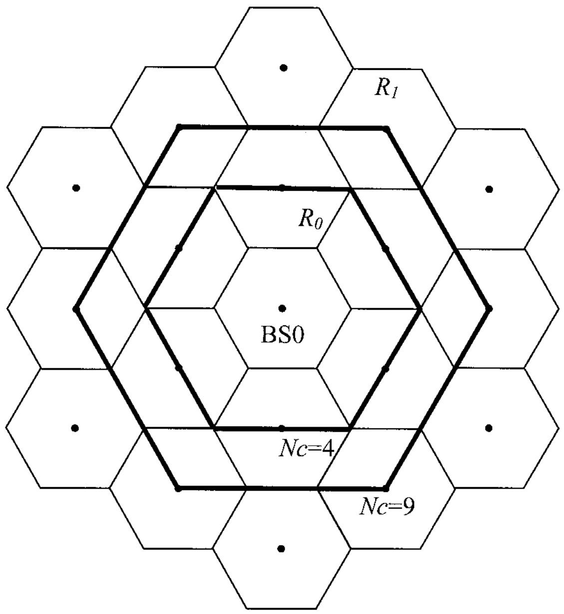

Fig. 1. Cellular system.

trol errors on cellular CDMA systems with fast power control and minimum attenuation based cell selection, explicitly taking into account the effects of multipath fading. Interference statistics are closely related to power control. The impact of fast power control on both intercell and intracell interference statistics is also analyzed. The results obtained are used to estimate system capacity.

This paper is organized as follows. The system model is presented in Section II. The derivation of intercell and intracell interference statistics is provided in Sections III and IV, respectively, for a system with imperfect fast power control and multipath fading. Section V presents an approximation of the average bit error rate (BER) in terms of processing gain and power control error deviation. Section VI provides the calculation of outage probability. In Section VII numerical results are displayed showing system capacity in terms of average BER and in terms of outage probability. Finally, concluding remarks are made in Section VIII.

II. System Model

A two-dimensional (2-D) layout of hexagonal cells with a base station located at the centre of every cell is assumed, as shown in Fig. 1. We consider a power-controlled direct sequence CDMA system with frequency duplex division, i.e., the forward and and reverse links are allocated to different bands. In the following, we will focus our attention on the reverse link.

The radio channel in our system is affected by long- and short-term fluctuations. Long- term fluctuations are due to shadowing and distance variations, while short-term fluctuations are due to multipath fading. The channel propagation gain between mobile i and base station j will thus be given by

$$G_{ij} = \frac{\chi_{Fij}}{d_{ij}^{\mu} 10^{\frac{\xi_{ij}}{10}}} \tag{1}$$

where d_{ij} is the distance between mobile i and base station j, μ is the path-loss exponent, ξ_{ij} is a random variable modeling the shadowing effect between mobile i and base station j, which is assumed to follow a Gaussian distribution with mean 0 and deviation σ_C; and χ_{Fij} is a random variable modeling the multipath fading process between mobile i and base station j. We assume that multipath propagation results in the reception of M equal strength paths with Rayleigh distribution, and RAKE receivers with M fingers are assumed to optimally combine the individual paths. The power of the multipath fading will thus have a chi-squared distribution with $2M$ degrees of freedom, with probability density function (pdf) [18]

$$f_{\chi_F}(x) = \frac{M^M}{(M-1)!} x^{M-1} e^{-Mx}. \tag{2}$$

Every base station transmits a pilot signal. Mobiles connect to the base station whose pilot signal is received with the highest average power level. Time averaging of these signals removes the rapid fluctuations due to multipath fading and these fluctuations are, therefore, not considered in the selection of base station. Hence, a user will connect to the base station toward which average attenuation is minimum.

We analyze the system performance at the central base station, denoted by BS0. The interference at BS0 is due to the mobiles over the whole service area. A system with N interfering users per cell is considered. As a given mobile may not be able to measure the pilot signals of all the base stations in the system, the selection will be considered as limited to the N_c nearest base stations. The selection among the nearest N_c base stations can also be justified by the use of neighbor cell lists by the users, where mobiles are regularly provided with a list of handover candidates to be monitored. As a result, the area of the system will be divided into two regions, as shown in Fig. 1: region R_0, which contains the points having BS0 among the N_c nearest base stations; and region R_1, which contains the points not having BS0 among the N_c nearest base stations. The size and the shape of these regions are a function of N_c and will be different in different environments due to shadow fading correlation. Ignoring this effect, in Fig. 1 it is shown the cases for $N_c = 4$ and $N_c = 9$.

Power control is considered to be fast enough that the rapid fluctuations in radio channel due to multipath fading are compensated. However, variations in the received power levels exist in any practical CDMA system since fluctuations of the radio channel cannot be perfectly compensated. For this reason, our analysis takes into account the effects of power level variations at the receiver in order to quantify the required accuracy of power control in CDMA systems.

III. Intercell Interference Statistics

Usually, imperfections in power control after despreading are modeled as a log-normal random variable [12]–[15]. Recently, in [11] it has been analytically verified that this assumption is a reasonable good one. Therefore, the power S_{Tk} received at a base station from a mobile k connected to it can be written as follows:

$$S_{T_k} = S \cdot 10^{\frac{\theta_k}{10}} = S \cdot e^{\beta \cdot \theta_k} \tag{3}$$

where $\beta = \ln(10)/10$; θ_k is a Gaussian random variable with mean 0 and standard deviation σ_θ for every mobile k and represents the desired user signal power variations, measured in dB, and S is the desired signal level. That is, the received signal powers at a given base station from mobiles connected to it will be independent and identically distributed (i.i.d.) log-normal random variables. The normalized interference at BS0 due to an active mobile k located at point (x,y) in the region R_1 will be given by

$$\left(\frac{I_{\text{out}}^{(k)}}{S}\right)_{R_1} = \left[\frac{\overset{Nc}{\underset{i=1}{Min}}\left(d_{ki}^{\mu}(x,y)10^{\frac{\xi_{ki}}{10}}\right)}{\chi_{Fki}}\right]\cdot\left[\frac{\chi_{Fk0}}{d_{k0}^{\mu}(x,y)10^{\frac{\xi_{k0}}{10}}}\right]\cdot e^{\beta\cdot\theta_k} \tag{4}$$

where the first factor is due to the compensation of radio channel variations (including multipath fading) at the base station to which the mobile is connected, the second factor is due to channel variations between the mobile and BS0 and the third factor is due to imperfections in power control. Considering statistically independent random variables, it can be found that the moment of order n of the interference generated by an active mobile k in region R_1 will be given by

$$\mathrm{E}\left[\left(\frac{I_{\text{out}}^{(k)}}{S}\right)^n\right]_{R_1} = \mathrm{E}\left[e^{n\lambda_{R_1}^{(k)}}\right]\mathrm{E}\left[(\chi_{Fk0})^n\right] \times\mathrm{E}\left[\left(\frac{1}{\chi_{Fki}}\right)^n\right]\mathrm{E}\left[e^{n\cdot\beta\cdot\theta_k}\right] \tag{5}$$

with

$$\lambda_{R_1}^{(k)} = -\beta\xi_{k0} + \overset{Nc}{\underset{i=1}{\mathrm{Min}}}\left(\mu\ln\frac{d_{ki}}{d_{k0}} + \beta\xi_{ki}\right). \tag{6}$$

Dependence on point (x,y) has been omitted for the sake of clarity. The first factor in (5) can be found to be given by [15], [19]

$$\mathrm{E}\left[e^{n\lambda_{R_1}^{(k)}}\right] = e^{n^2\beta^2\sigma_C^2}\sum_{i=1}^{Nc}\left(\frac{d_{ki}}{d_{k0}}\right)^{n\mu}\int_{-\infty}^{\infty}\frac{e^{-\frac{y^2}{y}}}{\sqrt{2\pi}} \cdot\prod_{\substack{j=1\\ j\neq i}}^{Nc} Q\left(y + \frac{\mu}{\beta\sigma_C}\ln\frac{d_{ki}}{d_{kj}} + n\beta\sigma_C\right)dy \tag{7}$$

with

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}dt. \tag{8}$$

The second and third factors in (5) can be found by simply solving the following integrals

$$\mathrm{E}\left[(x_{Fk0})^n\right] = \int_0^{\infty} x^n f_{x_F}(x)dx = \prod_{i=1}^{n}\frac{M+i-1}{M} \tag{9}$$

$$\mathrm{E}\left[\left(\frac{1}{x_{Fki}}\right)^n\right] = \int_0^{\infty}\frac{1}{x^n}f_{x_F}(x)dx = \prod_{i=1}^{n}\frac{M}{M-i} \tag{10}$$

And finally, the fourth factor can be calculated as

$$\mathrm{E}[e^{n\cdot\beta\cdot\theta_k}] = e^{n^2\cdot\beta^2\cdot\frac{\sigma_\theta{}^2}{2}} \tag{11}$$

Note that (10) is the moment of order n of the power transmitted by a mobile to compensate the multipath fading at the base station to which it is connected. For $M=1$ and $M=2$, it is clear from (10) that the mean and variance, respectively, of the interference at BS0 will be infinite. This would be the case if there were no limit in the power transmitted by mobiles to compensate multipath fading. In practice, however, this power is limited to a value P_M, and very deep fades will not be compensated. In this paper, in order to obtain expressions in a compact form, the number of resolvable paths is considered as higher than two, and the power transmitted by mobiles is not limited. In [20], we analyze the effect of transmitted power limit on CDMA systems with base station diversity.

On the other hand, a mobile located at the region R_0 can generate both intercell and intracell interference as a function of the base station to which it is connected. If the mobile is not connected to BS0, the normalized intercell interference generated by an active mobile k located at point (x,y) in region R_0 will be given by

$$\left(\frac{I_{\text{out}}^{(k)}}{S}\right)_{R_0} = \left[\frac{\overset{Nc-1}{\underset{i=1}{Min}}\left(d_{ki}^{\mu}(x,y)10^{\frac{\xi_{ki}}{10}}\right)}{\chi_{Fki}}\right]\cdot\left[\frac{\chi_{Fk0}}{d_{k0}^{\mu}(x,y)10^{\frac{\xi_{k0}}{10}}}\right]\cdot e^{\beta\cdot\theta_k} \tag{12}$$

where the minimum is now evaluated among the N_c-1 nearest base stations, excluding BS0. The normalized intercell interference given in (12) is valid if the following inequality holds

$$\frac{\overset{Nc-1}{\underset{i=1}{Min}}\left(d_{ki}^{\mu}(x,y)10^{\frac{\xi_{ki}}{10}}\right)}{d_{ki}^{\mu}(x,y)10^{\frac{\xi_{k0}}{10}}} < 1 \tag{13}$$

That is, the average attenuation to the base station to which the mobile is connected must be lower than the average attenuation to BS0 for a mobile in region R_0 to generate intercell interference. If inequality (13) does not hold, the mobile will switch to BS0 and will generate intracell interference. Note that condition (13) is equivalent to

$$\lambda_{R_0}^{(k)} < 0 \tag{14}$$

with

$$\lambda_{R_0}^{(k)} = -\beta\xi_{k0} + \overset{Nc-1}{\underset{i=1}{Min}}\left(\mu\ln\frac{d_{ki}}{d_{k0}} + \beta\xi_{ki}\right). \tag{15}$$

Therefore, the moment of order n of the intercell interference generated by an active mobile k located in region R_0 will be given by

$$\mathrm{E}\left[\left(\frac{I_{\text{out}}^{(k)}}{S}\right)^n\right]_{R_0} = \mathrm{E}\left[e^{n\lambda_{R_0}^{(k)}}\middle|\lambda_{R_0}^{(k)}<0\right]\cdot\mathrm{E}\left[(\chi_{Fk0})^n\right] \cdot\mathrm{E}\left[\left(\frac{1}{\chi_{Fki}}\right)^n\right]\cdot\mathrm{E}[e^{n\cdot\beta\cdot\theta_k}]. \tag{16}$$

The second, third, and fourth factors in (16) are the same as those calculated in (9)–(11), and the first factor can be shown to be given by [15], [19]

$$\mathrm{E}\left[e^{n\lambda_{R_0}^{(k)}}\middle|\lambda_{R_0}^{(k)}<0\right] = e^{n^2\beta^2\sigma_C^2}\sum_{i=1}^{Nc-1}\left(\frac{d_{ki}}{d_{k0}}\right)^{n\mu}\int_{-\infty}^{\infty}\frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \cdot Q\left(y+\frac{\mu}{\beta\sigma_C}\ln\frac{d_{ki}}{d_{k0}}+2n\beta\sigma_C\right) \cdot\prod_{\substack{j=1\\ j\neq i}}^{Nc-1}Q\left(y+\frac{\mu}{\beta\sigma_C}\ln\frac{d_{ki}}{d_{kj}}+n\beta\sigma_C\right)dy. \tag{17}$$

Now the mean and variance of the total intercell interference at BS0 can be derived. Assuming a uniform density of mobile users, N interfering users per cell and hexagonal cells with radius normalized to unity, the density of users is

$$\rho = \frac{2N}{3\sqrt{3}} \text{ users per unit area.} \tag{18}$$

To evaluate the average normalized intercell interference we must add the contribution of interference of all the active users in the service area not connected to BS0, that is

$$\mathrm{E}\left[\frac{I_{\text{out}}}{S}\right] = \iint_{R_0} \eta \mathrm{E}\left[\frac{I_{\text{out}}^{(k)}}{S}\right]_{R_0} \rho dA_0 + \iint_{R_1} \eta \mathrm{E}\left[\frac{I_{\text{out}}^{(k)}}{S}\right]_{R_1} \rho dA_1 \tag{19}$$

where A_0 and A_1 are, respectively, the areas of regions R_0 and R_1, and η is the probability that a given mobile is active. The average intercell interference will thus be given by

$$\mathrm{E}\left[\frac{I_{\text{out}}}{S}\right] = \eta \cdot \frac{M}{M-1} \cdot f \cdot N \cdot e^{\beta^2 \cdot \frac{\sigma_0{}^2}{2}} \tag{20}$$

where

$$\begin{aligned} f = {} & \frac{e^{\beta^2\sigma_C^2}}{N} \iint_{R_1} \\ & \times \left[\sum_{i=1}^{Nc} \left(\frac{d_{ki}}{d_{k0}}\right)^{\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \\ & \left. \cdot \prod_{\substack{j-1 \\ j\neq i}}^{Nc} Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{k0}} + \beta\sigma_C\right) dy \right] \rho dA_1 \\ & + \frac{e^{\beta^2\sigma_C^2}}{N} \iint_{R_0} \\ & \times \left[\sum_{i=1}^{Nc-1} \left(\frac{d_{ki}}{d_{k0}}\right)^{\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \\ & \cdot Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{k0}} + 2\beta\sigma_C\right) \\ & \left. \cdot \prod_{\substack{j-1 \\ j\neq i}}^{Nc-1} Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{kj}} + \beta\sigma_C\right) dy \right] \\ & \times \rho dA_0. \end{aligned} \tag{21}$$

On the other hand, the variance of the intercell interference at BS0 from a single user k will be

$$\begin{aligned} \mathrm{Var}\left(\frac{I_{\text{out}}^{(k)}}{S}\right)_{R_i} &= \eta \mathrm{E}\left[\left(\frac{I_{\text{out}}^{(k)}}{S}\right)^2\right]_{R_i} \\ & -\eta^2 \mathrm{E}^2\left[\frac{I_{\text{out}}^{(k)}}{S}\right]_{R_i}, \quad i = 0, 1. \end{aligned} \tag{22}$$

Assuming spatial whiteness for the shadowing variables at different locations, as in [1], the variance of the total interference at BS0 can be calculated

$$\begin{aligned} \mathrm{Var}\left(\frac{I_{\text{out}}}{S}\right) = {} & \iint_{R_0} \mathrm{Var}\left(\frac{I_{\text{out}}^{(k)}}{S}\right)_{R_0} \rho dA_0 \\ & + \iint_{R_1} \mathrm{Var}\left(\frac{I_{\text{out}}^{(k)}}{S}\right)_{R_1} \rho dA_1 \end{aligned} \tag{23}$$

And, hence, we obtain

$$\begin{aligned} \mathrm{Var}\left(\frac{I_{\text{out}}}{S}\right) = {} & \eta \cdot \frac{M(M+1)}{(M-1)(M-2)} \cdot g \cdot N \cdot e^{2\cdot\beta^2\cdot\sigma_0{}^2} \\ & -\eta^2 \cdot \frac{M^2}{(M-1)^2} \cdot h \cdot N \cdot e^{\beta^2\cdot\sigma_0{}^2} \end{aligned} \tag{24}$$

where

$$\begin{aligned} g = {} & \frac{e^{4\beta^2\sigma_C^2}}{N} \iint_{R_1} \\ & \times \left[\sum_{i=1}^{Nc} \left(\frac{d_{ki}}{d_{k0}}\right)^{2\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \\ & \left. \cdot \prod_{\substack{j-1 \\ j\neq i}}^{Nc} Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{kj}} + 2\beta\sigma_C\right) dy \right] \rho dA_1 \\ & + \frac{e^{4\beta^2\sigma_C^2}}{N} \iint_{R_0} \\ & \times \left[\sum_{i=1}^{Nc-1} \left(\frac{d_{ki}}{d_{k0}}\right)^{2\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \\ & \cdot Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{k0}} + 4\beta\sigma_C\right) \\ & \left. \cdot \prod_{\substack{j-1 \\ j\neq i}}^{Nc-1} Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{kj}} + 2\beta\sigma_C\right) dy \right] \\ & \times \rho dA_0 \end{aligned} \tag{25}$$

$$\begin{aligned} h = {} & \frac{e^{2\beta^2\sigma_C^2}}{N} \iint_{R_1} \\ & \times \left[\sum_{i=1}^{Nc} \left(\frac{d_{ki}}{d_{k0}}\right)^{\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \\ & \left. \cdot \prod_{\substack{j-1 \\ j\neq i}}^{Nc} Q\left(y + \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{kj}} + \beta\sigma_C\right) dy \right]^2 \rho dA_1 \\ & + \frac{e^{2\beta^2\sigma_C^2}}{N} \iint_{R_0} \\ & \times \left[\sum_{i=1}^{Nc-1} \left(\frac{d_{ki}}{d_{k0}}\right)^{\mu} \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \right. \end{aligned}$$

TABLE I
INTERFERENCE FACTOR f FOR DIFFERENT VALUES OF SYSTEM PARAMETERS

		σ_C = 4 dB	σ_C = 6 dB	σ_C = 6.3 dB	σ_C = 8 dB	σ_C = 10 dB
μ=3	Nc=4	0.9829	1.2789	1.3534	2.1059	4.8344
	Nc=9	0.9767	1.1584	1.1919	1.4661	2.2561
μ=4	Nc=4	0.4890	0.5844	0.6071	0.8364	1.6841
	Nc=9	0.4887	0.5658	0.5798	0.6801	0.9242
μ=5	Nc=4	0.3147	0.3514	0.3598	0.4395	0.7323
	Nc=9	0.3147	0.3487	0.3552	0.3999	0.4887

TABLE II
INTERFERENCE FACTOR g FOR DIFFERENT VALUES OF SYSTEM PARAMETERS

		σ_C = 4 dB	σ_C = 6 dB	σ_C = 6.3 dB	σ_C = 8 dB	σ_C = 10 dB
μ=3	Nc=4	0.2855	0.8592	1.2185	19.593	$1.7{\cdot}10^3$
	Nc=9	0.2756	0.4041	0.4591	2.3316	84.067
μ=4	Nc=4	0.1712	0.2662	0.3248	3.5570	318.33
	Nc=9	0.1707	0.2013	0.2102	0.4643	12.929
μ=5	Nc=4	0.1263	0.1462	0.1570	0.7576	63.835
	Nc=9	0.1263	0.1373	0.1399	0.1821	2.1283

$$\cdot Q\left(y+\frac{\mu}{\beta\sigma_C}\ln\frac{d_{ki}}{d_{k0}}+2\beta\sigma_C\right)$$
$$\left.\cdot\prod_{\substack{j=1\\ j\neq i}}^{Nc-1} Q\left(y+\frac{\mu}{\beta\sigma_C}\ln\frac{d_{ki}}{d_{kj}}+\beta\sigma_C\right)dy\right]^2$$
$$\times\,\rho dA_0. \qquad (26)$$

The integrals derived in this section must be solved numerically over the whole service area. The integrations involve finding the distance to BS0 and to the N_c (or N_c-1) nearest base stations for each point. Tables I- III provide, respectively, the values obtained for the interference factors f, g, and h for different values of the path loss exponent μ and deviation of the log-normal shadowing σ_C for $N_c=4$ and $N_c=9$. For the results shown, we have considered a system with 91 cells, corresponding to the central cell plus the closest five rings of cells surrounding the central base station. The validity of the numerical results has been supported by simulation. Our results show that, as expected, both the average intercell interference (which is proportional to f) and variance (which is a function of g and h) increase as μ decreases due to the decrement of the average attenuation. On the other hand, as σ_C increases the influence of distant users become dominant, which increases the intercell interference statistics. These results are consistent with the results in [15], where the mean and variance of the intercell interference are calculated for the nonmultipath case.

Our results have been obtained by considering uncorrelated shadowing between a mobile and the set of N_c base stations to which the mobile can connect. In a more general model, shadowing is assumed to be the product of two log-normal components: a component common to all the base stations specific to the location of the mobile, and a component which pertains solely to the receiving base station and is independent from

TABLE III
INTERFERENCE FACTOR h FOR DIFFERENT VALUES OF SYSTEM PARAMETERS

		σ_C = 4 dB	σ_C = 6 dB	σ_C = 6.3 dB	σ_C = 8 dB	σ_C = 10 dB
μ=3	Nc=4	0.1079	0.1070	0.1115	0.2060	1.0897
	Nc=9	0.1076	0.0930	0.0915	0.0902	0.1441
μ=4	Nc=4	0.0659	0.0549	0.0544	0.0639	0.2134
	Nc=9	0.0660	0.0540	0.0528	0.0477	0.0500
μ=5	Nc=4	0.0484	0.0379	0.0369	0.0343	0.0585
	Nc=9	0.0484	0.0380	0.0369	0.0323	0.0294

one base station to another. The inclusion of this assumption in the derived expressions is straightforward, and may be accomplished by substituting σ_C by $\sqrt{1-\Gamma}\cdot\sigma_C$ in the expressions of the normalized interference statistics, where Γ is the correlation coefficient of the shadowing between a mobile and two different base stations [19].

IV. INTRACELL INTERFERENCE STATISTICS

When imperfections in power control are considered, multipath fading is not perfectly compensated. As a result, the power received from a mobile will not be constant at the base station to which the mobile is connected. Thus, the normalized intracell interference generated at BS0 by an active mobile k located at point (x,y) in region R_0 (note that mobiles in the region R_1 cannot generate intracell interference) will be given by

$$\frac{I_{\text{in}}^{(k)}}{S}=\psi^{(k)}\cdot e^{\beta\cdot\theta_k} \qquad (27)$$

where $\psi^{(k)}$ is a Bernoulli distributed random variable taking values 0 (the mobile k is not connected to BS0) and 1 (the mobile k is connected to BS0), with $P(\psi^{(k)}=1)=\phi^{(k)}$. Therefore, $\phi^{(k)}$ represents the probability that mobile k is connected to BS0. Thus, the moment of order n of the intracell interference generated by an active user k will be given by

$$\mathrm{E}\left[\left(\frac{I_{\text{in}}^{(k)}}{S}\right)^n\right]=\phi^{(k)}\cdot e^{n^2\cdot\beta^2\cdot\frac{\sigma_Q{}^2}{2}}. \qquad (28)$$

We must then calculate the probability that a mobile is connected to BS0. In general, this probability is different for every mobile since it depends on the attenuation to BS0. Considering that a mobile can connect to the N_c nearest base stations, we can write

$$\phi^{(k)}=P\left(d_{k0}^{\mu}(x,y)\cdot 10^{\frac{\xi_{k0}}{10}}<\underset{i=1}{\overset{Nc-1}{Min}}\left(d_{ki}^{\mu}(x,y)10^{\frac{\xi_{ki}}{10}}\right)\right). \qquad (29)$$

That is, a mobile k will connect to BS0 if the average attenuation to BS0 is lower than the attenuation to the N_c-1 nearest base stations excluding BS0. We can rewrite (29) as

$$\phi^{(k)}=P\left(\lambda_{R_0}^{(k)}>0\right) \qquad (30)$$

where $\lambda_{R_0}^{(k)}$ is defined as in (15). Therefore, the probability that a mobile k located in region R_0 is connected to BS0 can be found using the following relations

$$\begin{aligned}\phi^{(k)} &= P\left(\lambda_{R_0}^{(k)} > 0\right)\\ &= P\left[-\beta\xi_{k0} + \underset{i=1}{\overset{Nc-1}{Min}}\left(\mu \ln \frac{d_{ki}}{d_{k0}} + \beta\xi_{ki}\right) > 0\right]\\ &= P\left[\mu \ln \frac{d_{k1}}{d_{k0}} + \beta\xi_{k1} > \beta\xi_{k0}\ldots,\right.\\ &\qquad \left.\mu \ln \frac{d_{k(Nc-1)}}{d_{k0}} + \beta\xi_{k(Nc-1)} > \beta\xi_{k0}\right] \end{aligned} \quad (31)$$

yielding, after straightforward manipulation

$$\phi^{(k)} = \int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \cdot \prod_{i=1}^{Nc-1} Q\left(y - \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{k0}}\right) dy. \quad (32)$$

The normalized average total intracell interference can be found by integrating throughout R_0, that is

$$\mathrm{E}\left[\frac{I_{\text{in}}}{S}\right] = \iint_{R_0} \eta \cdot \phi^{(k)} \cdot e^{\beta^2 \cdot \frac{\sigma_0{}^2}{2}} \cdot \rho dA_0 = \eta \cdot N \cdot e^{\beta^2 \cdot \frac{\sigma_0{}^2}{2}}. \quad (33)$$

Note that our results show that the average intracell interference is not a function of the channel parameters such as μ or σ_C, as is expected in a system with equally loaded cells.

The variance of the total normalized intracell interference can be calculated as

$$\begin{aligned}\mathrm{Var}\left(\frac{I_{\text{in}}}{S}\right) = \iint_{R_0} &\left[\eta \cdot \phi^{(k)} \cdot e^{2\cdot\beta^2\cdot\sigma_0{}^2}\right.\\ &\left. -\eta^2 \cdot \left(\phi^{(k)}\right)^2 \cdot e^{\beta^2\cdot\sigma_0{}^2}\right] \rho dA_0. \end{aligned} \quad (34)$$

Using (32) and (34), we can write

$$\mathrm{Var}\left(\frac{I_{\text{in}}}{S}\right) = \eta \cdot N \cdot e^{2\cdot\beta^2\cdot\sigma_0{}^2} - \eta^2 \cdot q \cdot N \cdot e^{\beta^2\cdot\sigma_0{}^2} \quad (35)$$

where

$$q = \iint_{R_0} \left[\int_{-\infty}^{\infty} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} \cdot \prod_{i=1}^{Nc-1} Q\left(y - \frac{\mu}{\beta\sigma_C} \ln \frac{d_{ki}}{d_{k0}}\right) dy\right]^2 \rho dA_0. \quad (36)$$

Table IV presents several results obtained by numerically integrating (36) for different values of the system parameters. From our results it is clear that as μ increases or σ_C decreases the intracell interference variance decreases because fewer mobiles can connect to a distant base station.

V. Average Bit Error Rate Analysis

Once the mean and variance of both intercell and intracell interference have been found we need to approximate the total interference with a known distribution to evaluate the average BER and the outage probability. Both parameters will be used as the performance criteria to evaluate the loss in capacity due to power control errors. In this section, an accurate approximation for average BER is presented, while the estimation of the outage probability is considered in the next section.

TABLE IV
Interference Factor q for Different Values of System Parameters

		σ_C = 4 dB	σ_C = 6 dB	σ_C = 6.3 dB	σ_C = 8 dB	σ_C = 10 dB
μ=3	Nc=4	0.7327	0.6091	0.5930	0.5148	0.4477
	Nc=9	0.7291	0.5791	0.5575	0.4483	0.3522
μ=4	Nc=4	0.8004	0.6996	0.6851	0.6091	0.5356
	Nc=9	0.8001	0.6919	0.6748	0.5791	0.4778
μ=5	Nc=4	0.8406	0.7596	0.7475	0.6803	0.6091
	Nc=9	0.8406	0.7581	0.7452	0.6692	0.5791

With direct sequence BPSK of spreading bandwidth W and assuming a sinc chip shape, the following expression holds for the ratio of despread bit energy to interference density for a given desired user 0

$$\frac{E_b}{I_0} = \frac{\frac{S_{T_0}}{R_b}}{N_0 + \frac{(I_{\text{in}}+I_{\text{out}})}{W}} = \frac{\left(\frac{S}{R_b}\right) \cdot e^{\beta\cdot\theta_0}}{N_0 + \frac{(I_{\text{in}}+I_{\text{out}})}{W}} \quad (37)$$

where the self-interference from various multipath components have been neglected. R_b is the information bit rate and N_0 is the background noise power spectral density, which is assumed as negligible compared to the interference power density due to mobile users.

Simulation shows that the total interference is closer to a log-normal distribution rather than to a Gaussian one when fast power control is used in a system with multipath fading [2]. This deviation from the central limit theorem can be explained by the tracking of multipath fading by only a few users or even by a single dominant user. Therefore, we will model the total normalized interference by a log-normal random variable ξ whose mean and variance can be derived as follows:

$$\begin{aligned}\mathrm{E}[\xi] &= \mathrm{E}\left[\frac{(I_{\text{in}}+I_{\text{out}})}{S}\right] = \mathrm{E}\left[\frac{I_{\text{in}}}{S}\right] + \mathrm{E}\left[\frac{I_{\text{out}}}{S}\right]\\ &= \eta \cdot N \cdot e^{\beta^2\cdot\frac{\sigma_0{}^2}{2}} + \eta \cdot \frac{M}{M-1} \cdot f \cdot N \cdot e^{\beta^2\cdot\frac{\sigma_0{}^2}{2}} \end{aligned} \quad (38)$$

$$\begin{aligned}\mathrm{var}[\xi] &= \mathrm{var}\left[\frac{(I_{\text{in}}+I_{\text{out}})}{S}\right] = \mathrm{var}\left[\frac{I_{\text{in}}}{S}\right] + \mathrm{var}\left[\frac{I_{\text{out}}}{S}\right]\\ &= \eta \cdot N \cdot e^{2\cdot\beta^2\cdot\sigma_0{}^2} - \eta^2 \cdot q \cdot N \cdot e^{\beta^2\cdot\sigma_0{}^2}\\ &\quad + \eta \cdot \frac{M(M+1)}{(M-1)(M-2)} \cdot g \cdot N \cdot e^{2\cdot\beta^2\cdot\sigma_0{}^2}\\ &\quad - \eta^2 \cdot \frac{M^2}{(M-1)^2} \cdot h \cdot N \cdot e^{\beta^2\cdot\sigma_0{}^2}. \end{aligned} \quad (39)$$

Neglecting the background noise, (37) can be rewritten as

$$\frac{E_b}{I_0} = \frac{\left(\frac{W}{R_b}\right) \cdot e^{\beta\cdot\theta_0}}{\xi} = \frac{\left(\frac{W}{R_b}\right) \cdot e^{\beta\cdot\theta_0}}{e^{\Omega}} \quad (40)$$

where Ω is Gaussian distributed with mean and variance given by

$$m_\Omega = \frac{1}{2} \cdot \ln\left(\mathrm{var}[\xi] + \mathrm{E}^2[\xi]\right) - \sigma_\Omega{}^2 \quad (41)$$

$$\sigma_\Omega{}^2 = \ln\left(\mathrm{var}[\xi] + \mathrm{E}^2[\xi]\right) - 2 \cdot \ln\left(\mathrm{E}[\xi]\right). \quad (42)$$

The bit error probability P_e, for constant received signal power levels can be approximated, under the Gaussian assumption [21], by

$$P_e = Q\left(\sqrt{2\cdot\frac{E_b}{I_o}}\right). \tag{43}$$

As the desired signal is a log-normal random variable due to power control imperfections, the ratio E_b/I_o can be approximated by another log-normal random variable and therefore, we can write

$$P_e = Q(e^{\gamma}) \tag{44}$$

where γ is a Gaussian random variable with mean and variance given by

$$m_\gamma = \frac{1}{2}\cdot\ln\left(2\cdot\frac{W}{R_b}\right) - \frac{1}{2}\cdot m_\Omega \tag{45}$$

$$\sigma_\gamma{}^2 = \frac{1}{4}\cdot\left(\sigma_\Omega{}^2 + \beta^2\sigma_\theta{}^2\right) \tag{46}$$

in which m_Ω and $\sigma_\Omega{}^2$ are given by (41) and (42), respectively.

Averaging over γ, we can evaluate the average of the bit error probability, i.e.

$$\overline{P_e} = \int_{-\infty}^{\infty} Q(e^{\gamma})q(\gamma)d\gamma \tag{47}$$

where $g(\gamma)$ is the probability density function of γ. In [22] it is shown that if F is a real function of a random variable x with mean m and deviation σ, using an expansion in central differences (Stirling formula), the following approximation holds:

$$\mathrm{E}\left[F(x)\right] \approx F(m) + \frac{F(m+\sqrt{3}\sigma) - 2F(m) + F(m-\sqrt{3}\sigma)}{6}. \tag{48}$$

This approximation is exact if function F is a fifth degree polynomial and x is a Gaussian random variable, and it is fairly robust to deviations from those conditions. Using this approximation in (47), we obtain

$$\overline{P_e} \approx \frac{2}{3}\cdot Q(e^{m_\gamma}) + \frac{1}{6}\cdot Q(e^{m_\gamma+\sqrt{3}\sigma_\gamma}) + \frac{1}{6}\cdot Q(e^{m_\gamma-\sqrt{3}\sigma_\gamma}). \tag{49}$$

VI. Outage Probability Analysis

An outage will be considered to occur when the BER is higher than a given required value α. Therefore, the probability of outage can be written as

$$P_{\text{out}} = P(P_e \geq \alpha) = 1 - F_{P_e}(\alpha) \tag{50}$$

where $F_{P_e}(x)$ is the cumulative distribution function (cdf) of the BER. Taking into account (44), $F_{P_e}(x)$ can be expressed as

$$\begin{aligned} F_{P_e}(x) &= P(P_e < x) = P\left(Q(e^{\gamma}) < x\right) \\ &= P\left(e^{\gamma} \geq Q^{-1}(x)\right) \\ &= P\left(\gamma \geq \ln\left(Q^{-1}(x)\right)\right) \\ &= 1 - F_\gamma\left(\ln\left(Q^{-1}(x)\right)\right) \end{aligned} \tag{51}$$

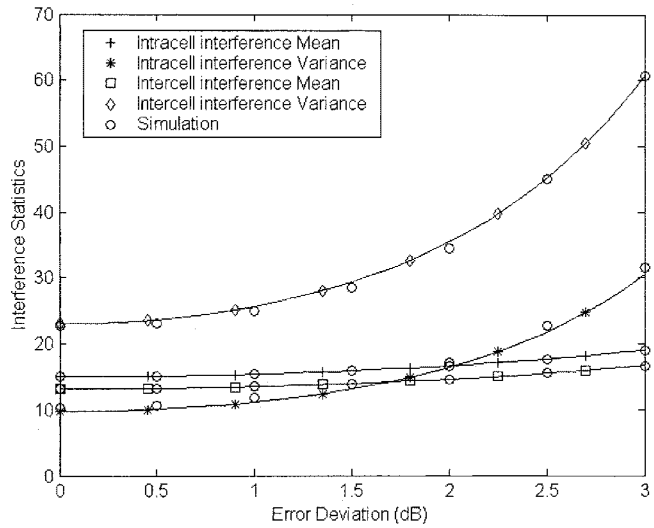

Fig. 2. Influence of power control error on interference statistics ($N = 30$, $M = 3$, $\mu = 4$, $\sigma_C = 6$ dB, $N_c = 4$, $\eta = 0.5$).

where $F_\gamma(x)$ is the cdf of a Gaussian random variable with mean and variance given by (45) and (46), respectively. Hence, we can write

$$F_{P_e}(x) = Q\left(\frac{\ln\left(Q^{-1}(x)\right) - m_\gamma}{\sigma_\gamma}\right). \tag{52}$$

Substituting (52) in (50) yields the outage probability

$$P_{\text{out}} = 1 - Q\left(\frac{\ln\left(Q^{-1}(\alpha)\right) - m_\gamma}{\sigma_\gamma}\right). \tag{53}$$

VII. Numerical Results

In this section, curves are presented showing the results obtained for the system capacity, first in terms of average error rate, and second, in terms of outage probability. Numerical results are also given for systems with different processing gains showing the reductions in system capacity due to imperfect power control. For all the following figures the parameters considered by default are: a processing gain ($G_p = W/R_b$) of 512, a path loss exponent of 4, three equal strength resolvable paths with Rayleigh distribution and $N_c = 4$, i.e., a mobile user can connect to one of the four nearest base stations.

Fig. 2 shows the intracell and intercell interference statistics (mean and variance) as a function of power control error considering the probability of a given mobile user being active to be 50%. It can be observed that the interference variance is greatly affected by power control imperfections. The presented numerical results have been validated by Monte Carlo simulation. It is clear that simulation results agree with our analytical model with great accuracy. From this figure we can conclude that the usual approach of considering that the intercell interference is a fraction of the intracell interference (see, for example, [13]) results in an important underestimation of the intercell interference variance, leading to very optimistic results [16], [17]

Simulations have also been obtained to validate our BER results as a function of the number of users per cell, as shown in Fig. 3. It is also shown in this figure BER results considering the

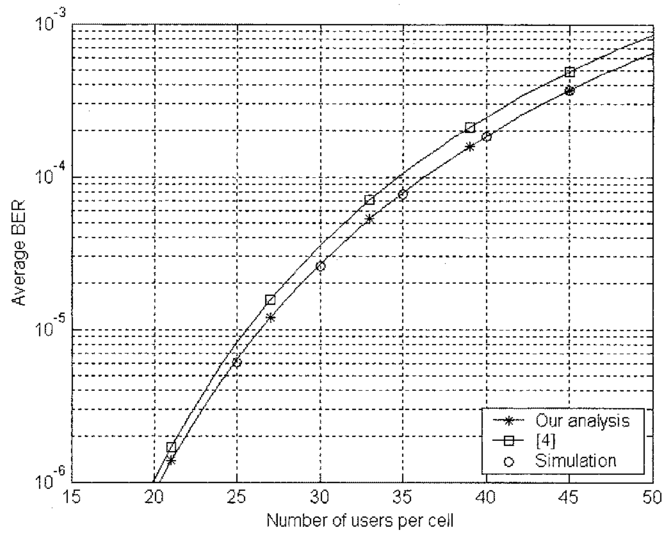

Fig. 3. Average BER versus number of users per cell. Comparison of results using the interference model from [4] with our model ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4, \sigma_\theta = 0.5$ dB, $\mathrm{G_p} = 512, \eta = 1$).

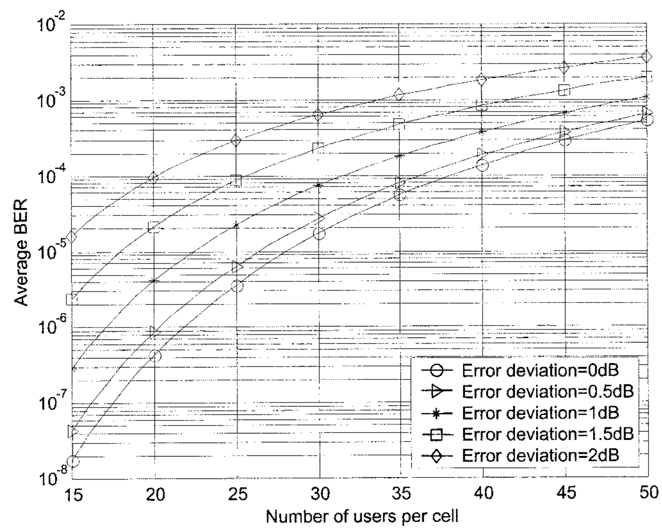

Fig. 4. Average BER for different values of power control error deviation ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4, \mathrm{G_p} = 512, \eta = 1$).

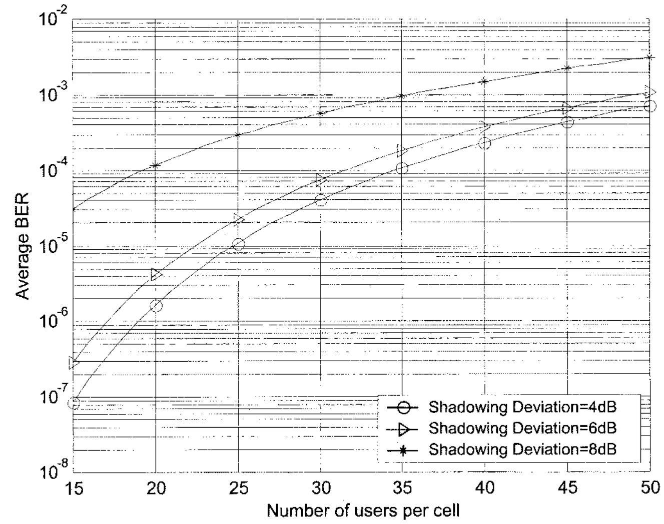

Fig. 5. Influence of log-normal shadowing deviation on average BER ($M = 3, \mu = 4, \sigma_\theta = 1$ dB, $N_c = 4, \mathrm{G_p} = 512, \eta = 1$).

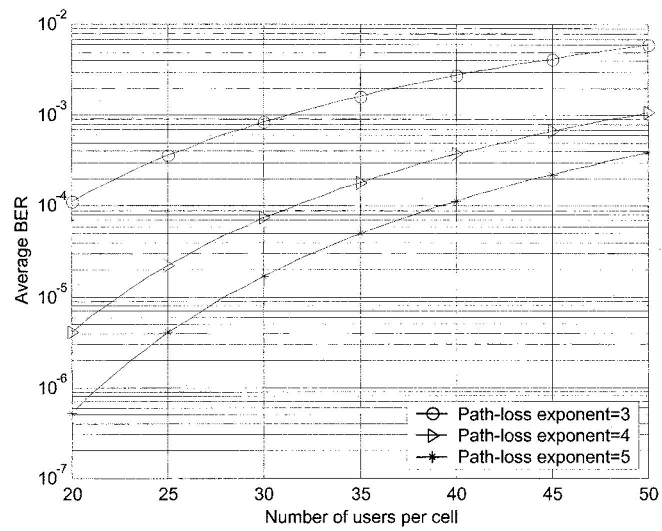

Fig. 6. Influence of path-loss exponent on average BER ($M = 3, \sigma_\theta = 1$ dB, $\sigma_C = 6$ dB, $\mathrm{N_c} = 4, \mathrm{G_p} = 512, \eta = 1$).

interference model used in [4], where it is assumed that users connect to the nearest base station or to the reference base station BS0. It can be seen that the latter approach overestimates the interference for the considered system parameters, yielding a higher BER.

Fig. 4 shows BER as a function of the number of users per cell for different power control errors. A 15% decrease in capacity can be seen for a required average BER of 10^{-4}, when power control error deviation increases from 0 dB (perfect power control) to 1 dB. It can also be seen that when the number of users is not too high, the average BER increases by about one order of magnitude if the error deviation in power control increases from 0 to 1 dB. However, when the number of users is higher, the average BER becomes less sensitive to imperfections of power control. This is because, for more active users in the system, the effect of the variance in signal power from different users tends to average out.

Other results displayed in Figs. 5 and 6 show the influence of channel propagation conditions (shadowing deviation, σ_C, and path-loss exponent, μ) on the average BER for a CDMA system with imperfect power control. In Fig. 5, it is seen that if σ_C increases from 6 to 8 dB, the number of users decreases by 38% for a required average BER of 10^{-4}, whereas if σ_C increases from 4 to 6 dB, the capacity decreases by approximately 11%. Fig. 6 shows that, as expected, an increase in the path-loss exponent entails a decrease in the intercell interference level and, therefore, an improvement in system performance.

Fig. 7 shows the degree of power control imperfections that can be tolerated while supporting a certain number of users at a prescribed average BER. As expected, system capacity decreases when power control is less effective and when quality of service requirements (in our case, the required average BER) are more exacting. Numerical results showing the system capacity from the point of view of outage probability are presented now. In our study, an outage will be considered to occur when the

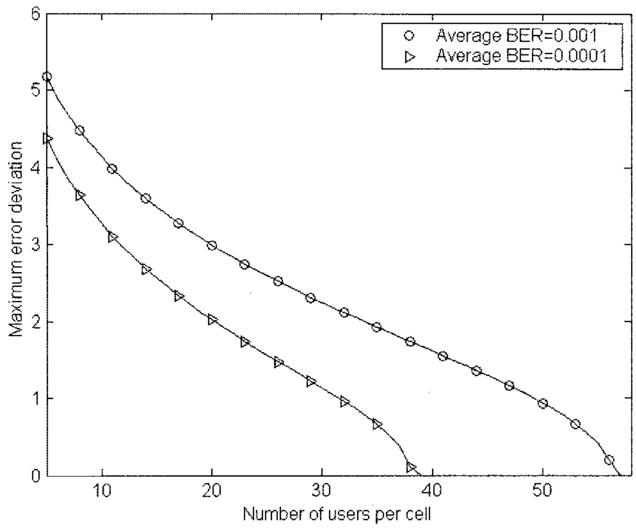

Fig. 7. Maximum error standard deviation in order to fulfill the required average BER ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4$, $G_p = 512, \eta = 1$).

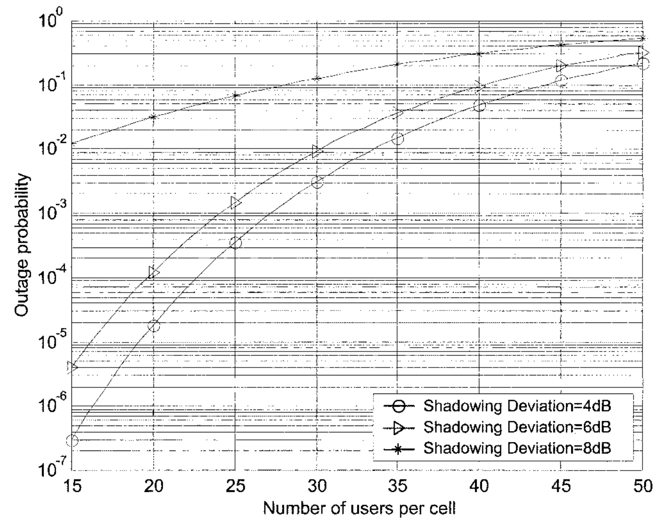

Fig. 9. Influence of log-normal shadowing deviation on outage probability ($M = 3, \mu = 4, \sigma_\theta = 1$ dB, $N_c = 4$, $G_p = 512, \eta = 1$).

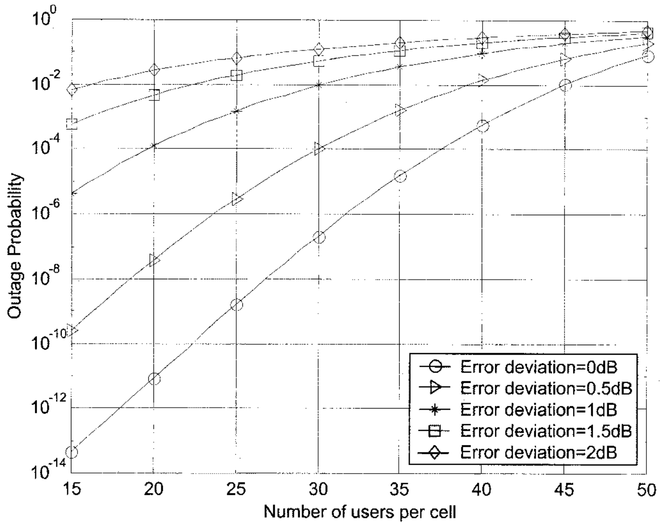

Fig. 8. Outage probability for different values of power control error deviation ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4$, $G_p = 512, \eta = 1$).

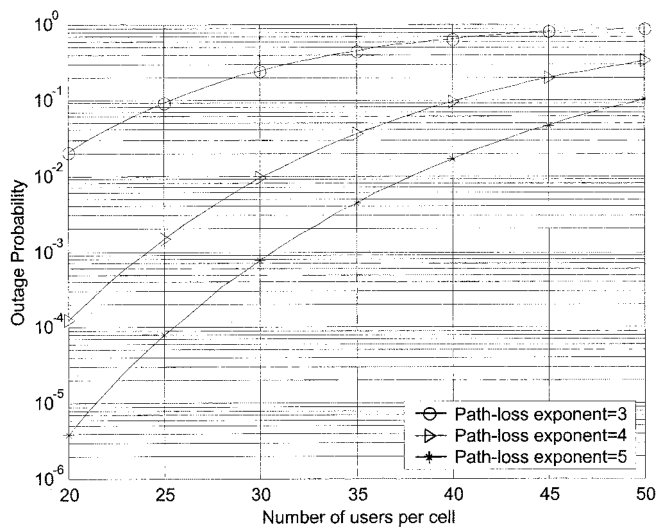

Fig. 10. Influence of path-loss exponent on outage probability ($M = 3, \sigma_\theta = 1$ dB, $\sigma_C = 6$ dB, $N_c = 4$, $G_p = 512, \eta = 1$).

BER exceeds a prescribed level. In our case, the target BER considered is 10^{-4}. Results for the outage probability for different numbers of users and different power control error deviations are provided in Fig. 8. In this figure, system capacity (defined as the number of users for an outage probability of 10^{-2}) can be seen to decrease by 33% when error deviation varies from 0 dB (perfect power control) to 1 dB. Furthermore, it can be seen that outage probability becomes more sensitive to imperfections of power control when the number of users is lower, in the same way as average BER does.

The effects of variations in channel propagation conditions (σ_C and μ) on outage probability for an error deviation of 1 dB can be seen in Figs. 9 and 10. The path loss exponent is shown to have a critical impact on capacity. We can also observe that for σ_C equal to 8 dB the maximum number of users per cell for 1% outage probability is reduced 50% with respect to the case when the shadowing deviation is equal to 6 dB.

A further result of interest would be to represent the degree of imperfection of power control that can be supported in order to maintain the outage probability below a prescribed level for a certain number of active users per cell. This result is shown in Fig. 11, where it can be seen that, to maintain the outage probability below 10%, the number of users allowed in the system decreases by 18% when σ_θ varies from 0 dB to 1 dB. Note that the decrease in capacity with power control error is faster when quality of service requirements are more exacting (there is a 33% decrease for a required outage probability of 1%).

The influence of the processing gain on system capacity is addressed now. The relationship between the BER and processing gain can be drawn from (43)–(46). This relationship has been used to obtain Figs. 12–14. Fig. 12 presents the number of users that the system can support when the average BER that a user experiences is no larger than 10^{-4}. It can be seen that the system capacity is approximately proportional to the processing gain (slightly higher to be exact), even with imperfect power con-

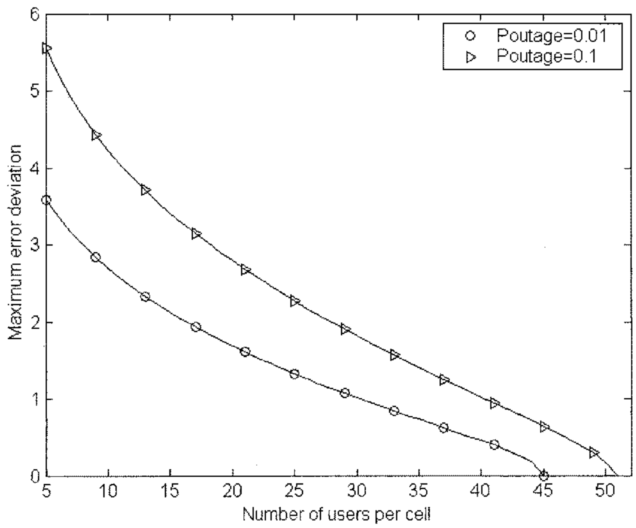

Fig. 11. Maximum error standard deviation to fulfill the required outage probability ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4$, $\mathrm{G_p} = 512, \eta = 1$).

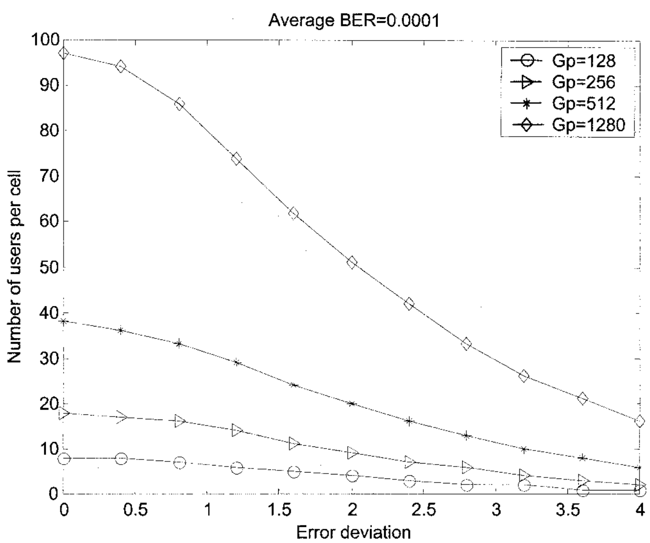

Fig. 12. Capacity in terms of average BER for different processing gains ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4, \eta = 1$).

trol. Fig. 13 presents the number of users that the system can sustain while maintaining an outage probability of 1%. Also, in this case, system capacity increases faster than linearly with processing gain. From Figs. 12 and 13, it can be seen that a higher $\mathrm{G_p}$ is affected by power control imperfections in a similar way than a lower $\mathrm{G_p}$ despite the increased number of active users and the averaging effect on power variations. This means that power variations of the desired user are the limiting factor in the system. On the other hand, if the processing gain is large and the power control is very accurate ($\sigma_\theta \approx 0$), the system capacity in terms of average BER is significantly lesser than the capacity in terms of outage probability. This result is consistent with the result in [12] for a single cell system and can be seen more clearly in Fig. 14 where, if the power control error deviation is small, capacity based on outage probability is greater than capacity based on average bit error rate, as a result of small fluctuations in BER. However, when error deviation is greater, there is an increase in the fluctuations in the error rate and, as

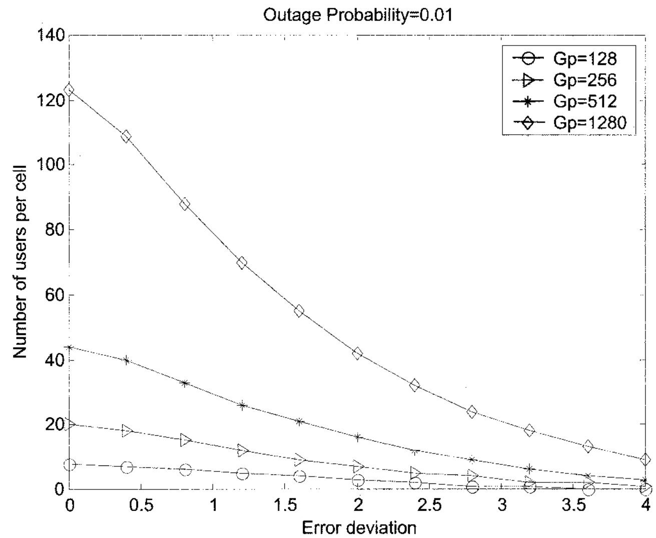

Fig. 13. Capacity in terms of outage probability for different processing gains ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4, \eta = 1$).

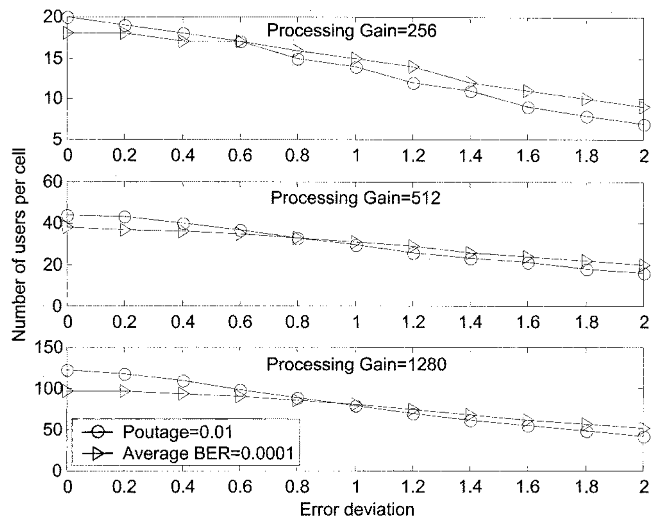

Fig. 14. System capacity for different processing gains and different criteria ($M = 3, \mu = 4, \sigma_C = 6$ dB, $N_c = 4, \eta = 1$).

a result, capacity based on outage probability is lesser than capacity based on average error rate.

VIII. Conclusion

In this paper, a theoretical analysis is provided for the impact of power control imperfections on the reverse link interference statistics and capacity of cellular direct sequence CDMA systems with fast power control and minimum attenuation based base station selection under multipath fading. Each multipath signal is assumed to undergo Rayleigh distribution and the system is considered to use RAKE diversity receivers. The mean and variance of both intracell and intercell interference have been accurately calculated with a reasonable amount of numerical complexity and the results have been used to estimate system capacity. Our results show that the variations in power level due to imperfections in power control have a detrimental effect on system performance. With a processing gain of 512, it was observed that a standard deviation of 1 dB in power level results in a 15% capacity reduction in terms of average error rate when the required BER is 10^{-4}. Under the same circumstances, in terms of outage probability system capacity is reduced 33% for a required outage probability of 10^{-2}. On the other hand, it was shown that both the average BER and the outage probability become less sensitive to power level variations with heavier traffic loads, that is, the increase in average error rate or in outage probability is faster in a system with lighter traffic when power control errors increase. The reason for this is that the effect of the variations in signal power from different users tends to average out. The variations in the desired user signal that have not been compensated by power control and not the variation in interference power have been found to be the limiting factor for multicell CDMA system capacity with imperfect power control.

It has also been observed that capacity based on outage probability is greater than capacity based on the average BER when error deviation is maintained below a given threshold as fluctuations in error rate in this case will be small. This threshold for error deviation increases with processing gain as expected. That is, if processing gain increases, the number of users can also increase and the fluctuations in BER decrease as a result of the averaging effect on power variations.

In conclusion, a significant improvement in system performance can be expected if power control is sufficiently effective, with even more pronounced benefits for a small number of users in the system.

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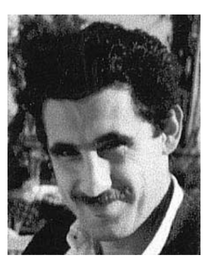

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