Reverse Link Capacity Analysis of Cellular CDMA Systems with Controlled Power Disparities and Successive Interference Cancellation

Hong Nie, *Member, IEEE,* P. Takis Mathiopoulos, *Senior Member, IEEE,* and George K. Karagiannidis, *Senior Member, IEEE*

***Abstract*— This paper presents a new approach in analyzing the reverse link capacity performance of cellular CDMA systems employing successive interference cancellation (SIC). Due to the controlled power disparity present in such systems previous methods cannot precisely model their inter-cell interference. We first introduce a novel model which allows the accurate analysis and evaluation of the inter-cell interference of cellular CDMA systems with controlled power disparity. Its validity is verified by means of theoretical analysis and computer simulations. Secondly, by using this new inter-cell interference model, a theoretical analysis of the CDMA reverse link capacity is presented. In terms of evaluation results, we focus on the performance improvements SIC offers as compared to single user detection (SUD). Analytical results complemented by equivalent computer simulated performance evaluation results have shown that SIC significantly increases the reverse link capacity of cellular CDMA systems operating in realistic controlled power disparity environments.**

***Index Terms*— Capacity improvement, CDMA, controlled power disparity, inter-cell interference, power control, reverse link, successive interference cancellation.**

I. Introduction

IN cellular code division multiple access (CDMA) systems the simplest technique to detect mobile users is single-user detection (SUD), i.e., each mobile user is detected independently without considering multiple access interference (MAI) [1],[2]. Although the implementation of SUD is simple, its ability to combat the MAI is weak [1], and hence the reverse link capacity of the systems employing SUD is seriously MAI restricted. In order to achieve higher system capacities within a limited radio frequency bandwidth, various multiuser detection techniques have been developed for base station (BS) receivers to reduce the effects of MAI [1]. Among these techniques, successive interference cancellation (SIC) is considered as one of the simplest, yet most robust methods [3]-[5]. As discussed in [4] and [5], when SIC is employed, mobile users assigned to the same BS are detected successively from the one with the minimum path loss (PL) to that with the maximum PL. Whenever a mobile user is detected, the interference produced by this mobile user is cancelled from the overall received signals. The remaining mobile users are then detected from the remaining received signals. Thus, mobile users who are detected subsequently suffer less MAI, and consequently the reverse link capacity of the systems can be increased. In order to investigate the improvements of the reverse link capacity achieved by the SIC, MAI must be first evaluated.

MAI can be categorized into two types of interference: intra-cell interference, i.e., the interference produced by other mobile users assigned to the same BS, and inter-cell interference, i.e., the interference produced by the mobile users assigned to other BSs [6]. It is well known that in order to reduce MAI of cellular CDMA systems, power control schemes must be employed to regulate the receiving powers of mobile users at their assigned BSs. Consequently, it is straightforward to derive the intra-cell interference from these receiving powers [7]. On the contrary, the derivation of inter-cell interference is more complex, especially when lognormal shadow fading is considered. When SUD is employed, in order to maintain the same signal-to-interference-plus-noise ratio (SINR) for all mobile users, power control must permit them to have the same receiving power at their assigned BSs [7].

In the past, numerous publications (e.g., [8]-[12]) have analyzed and evaluated the effects of inter-cell interference on the capacity of cellular CDMA systems. The most widely recognized inter-cell interference model, for which equal receiving power is assumed, was first proposed in [8] and then generalized in [9]. However, when SIC is considered, the mobile users who are subsequently detected suffer reduced MAI as compared to those detected earlier. Consequently, in order to maintain the same SINR for all mobile users, the employed power control scheme should allow the subsequently detected users to have lower receiving power than those detected earlier. With such *controlled power disparity*, the inter-cell interference model proposed in [8] and [9], cannot be used to evaluate inter-cell interference of the systems employing SIC.

To the best of our knowledge, in the past only few papers (e.g., [4], [5]) investigating the inter-cell interference of

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H. Nie is with the Department of Engineering, Cape Breton University, P. O. Box 5300, 1250 Grand Lake Road, Sydney, N.S., B1P6L2, Canada (e-mail: hong_nie@capebretonu.ca).

P. T. Mathiopoulos is with the Institute for Space Applications and Remote Sensing, National Observatory of Athens, Metaxa & Vas. Pavlou Street, Palea Penteli, 15236 Athens, Greece (e-mail: mathio@space.noa.gr).

G. K. Karagiannidis is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece (e-mail: geokarag@auth.gr).

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CDMA systems employing SIC have been published in the open technical literature. In these early publications inter-cell interference evaluation is simplified in two ways: *i*) by excluding the effects of lognormal shadow fading from the reverse link PL model and *ii*) by conveniently assuming the cells to be circles instead of the usual hexagonal shapes. However, as it will be shown later on in this paper, if the effects of lognormal shadow fading are not taken into account, the inter-cell interference is significantly underestimated. Furthermore, since the overlap between the considered circle-shaped cells is not accounted for, the methodology proposed in [4] and [5] is inaccurate. Thus, it cannot be used to precisely evaluate inter-cell interference even without considering shadow fading in the reverse link PL. On the contrary, in our paper by including the effects of lognormal shadow fading in the reverse link PL model and considering hexagonal cells we propose a novel model which precisely evaluates the inter-cell interference of the cellular CDMA systems with controlled power disparity. Furthermore, by employing this novel inter-cell interference model, we present a new approach thoroughly analyzing and accurately evaluating the reverse link capacity improvement obtained by employing SIC. Preliminary versions of our paper have been presented in [13] and [14].

The organization of the paper is as follows. After this introduction, Section II presents the system and PL model of the cellular CDMA system under consideration. The new inter-cell interference model for mobile users with controlled power disparities is presented in Section III. The individual inter-cell interference factors are analyzed in Section IV and in the following section the reverse link capacities of systems employing SUD and SIC are analyzed and evaluated. Various computer simulated performance results confirming the proposed analysis are presented in Section VI. Conclusions are summarized in Section VII.

II. System and Path-Loss Model

We consider a widely used cellular CDMA model (e.g., see [7]-[9]) consisting of M identical hexagonal cells, each having at its center a BS with an omni-directional antenna. It is assumed, without loss of generality, that the mobile users present in the system are independent and uniformly distributed in the total area of the M cells. It is thus reasonable to assume that there is an equal number of mobile users, denoted as N, assigned to each BS. Correspondingly, the number of mobile users per unit area, ρ, is given by

$$\rho = N/A_C \tag{1}$$

where A_C is the geographical area of one hexagonal cell. The PL from mobile users to BSs is assumed to satisfy the International Mobile Telecommunication 2000 (IMT-2000) propagation model, i.e., it includes distance attenuation and large scale fading (lognormal shadow fading) [15]. The distance attenuation[1], DA_m, from a mobile user to the m^{th} BS can be expressed as

$$DA_m = 10\mu \log_{10} r_m + D \tag{2}$$

[1]Unless otherwise stated, the values of the distance and large scale fading attenuations are given in dB.

where r_m is the distance from the mobile user to the m^{th} BS, μ is the distance attenuation exponent, and D is a constant attenuation common to all BSs. Moreover, the lognormal shadow fading, LSF_m, from the mobile user to the m^{th} BS is given by

$$LSF_m = ah + bh_m \tag{3}$$

where h and h_m are two independent and zero-mean Gaussian distributed random variables with standard deviation σ. In the above equation, a and b are two constants satisfying the condition $a^2 + b^2 = 1$, so that the standard deviation of LSF_m equals σ. Furthermore, on the one hand, the product ah represents the common to all BSs lognormal shadow fading caused by the obstacles close to the mobile user [8]. On the other hand, bh_m represents the independent from other BSs lognormal shadow fading caused by the obstacles close to the m^{th} BS [8]. From (3), the correlation of the lognormal shadow fading from a mobile user to any two BSs, denoted as CL_{mn}, can be expressed as

$$\begin{aligned} CL_{mn} &= \frac{E[LSF_m LSF_n]}{\sqrt{E[(LSF_m)^2]E[(LSF_n)^2]}} \\ &= \frac{E[(ah+bh_m)(ah+bh_n)]}{\sqrt{E[(ah+bh_m)^2]E[(ah+bh_n)^2]}} = a^2 \end{aligned} \tag{4}$$

where $E[\cdot]$ denotes the expected value of $[\cdot]$. Clearly, if $a = 0$ and $b = 1$, the lognormal shadow fading from a mobile user to the different BSs is independent from each other. On the contrary, if $a = 1$ and $b = 0$, the lognormal shadow fading from a mobile user to the different BSs is identical to each other. Using (2) and (3), the PL from a mobile user to the m^{th} BS, PL_m, can be expressed as follows

$$PL_m = DA_m + LSF_m = 10\mu \log_{10} r_m + ah + bh_m + D. \tag{5}$$

As discussed in [8], in order to reduce inter-cell interference, each mobile user should be assigned to the BS with the minimum PL instead of that with the minimum distance. However, as for large scale systems it might not be possible (computationally or otherwise) to consider all BSs of the entire network, it is reasonable to assume that for each mobile user only the closest N_C BSs are searched. From these N_C BSs that particular mobile user is assigned to the BS with minimum PL. Consequently, for each BS there exists a specific servicing area (SA) within which a mobile user can be assigned to that particular BS. As illustrated in Fig. 1, the geometrical area of such SAs (denoted in the figure as shaded areas) depends on the particular choice of N_C. For the convenience of the mathematical representation the central BS is denoted as the 0^{th} BS, and its corresponding SA as S_0. Obviously, the total area of S_0 is a function of N_C, i.e.

$$S_0 = N_C A_C. \tag{6}$$

Since each considered mobile user is assigned to the BS with the minimum PL among the N_C closest BSs, the PL from the mobile user to its assigned BS, denoted as PLU, is given by

$$PLU = \min_{j=1}^{N_C} \{PL_{m_j}\} \tag{7}$$

where $\{m_j, j \in [1, N_C]\}$ are the N_C nearest BSs to the mobile user. If a mobile user with physical location $(x, y) \in S_0$ is

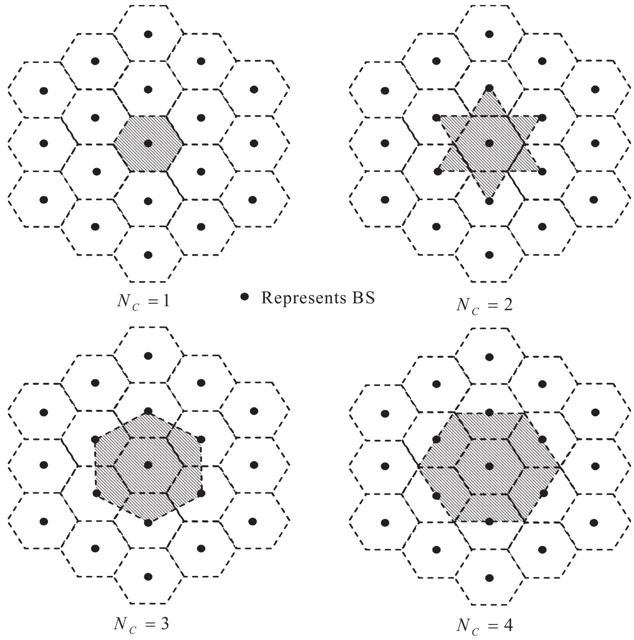

Fig. 1. Serving area of the central base station for different values of N_C.

assigned to the 0^{th} BS, the probability that its *PLU* is less than *K*, $\Pr\{PLU \le K\,|(x,y)\}$, can be found using (5) and (7) as

$$\begin{aligned}\Pr\{PLU \le K\,|(x,y)\} &= \Pr\{PL_0 \le K; PL_0 \le PL_i,\\ &\qquad \mathrm{i} \in [1,2,\ldots,N_C-1]\,|(x,y)\}\\ &= \Pr\left\{h_0 \le \frac{K-M_0-ah}{b}; h_i \ge \frac{bh_0+M_0-M_i}{b},\right.\\ &\qquad \left.\mathrm{i} \in [1,2,\ldots,N_C-1]\right\}\\ &= \int_{-\infty}^{+\infty} \frac{\exp\left(-h^2/2\sigma^2\right)}{\sqrt{2\pi}\sigma} \int_{-\infty}^{(K-M_0-ah)/b} \frac{\exp\left(-h_0^2/2\sigma^2\right)}{\sqrt{2\pi}\sigma}\\ &\qquad \prod_{i=1}^{N_C-1} Q\left(\frac{bh_0+M_0-M_i}{b\sigma}\right) dh_0 dh \end{aligned} \tag{8}$$

where $M_i = 10\mu\log_{10} r_i(x,y) + D$ and $Q(z) = \int_z^{+\infty} \exp\left(-\xi^2/2\right)/\left(\sqrt{2\pi}\right) d\xi$ is the well known Q-function. From (8) and (1), the cumulative probability function (CDF) of PLU, $F(K)$, can be expressed as

$$\begin{aligned}F(K) &= \frac{1}{N}\iint_{S_0} \Pr\{PLU \le K\,|(x,y)\}\rho dxdy\\ &= \frac{1}{A_C}\iint_{S_0}\int_{-\infty}^{+\infty} \frac{\exp\left(-h^2/2\sigma^2\right)}{\sqrt{2\pi}\sigma}\int_{-\infty}^{(K-M_0-ah)/b} \frac{\exp\left(-h_0^2/2\sigma^2\right)}{\sqrt{2\pi}\sigma}\\ &\qquad \prod_{i=1}^{N_C-1} Q\left(\frac{bh_0+M_0-M_i}{b\sigma}\right) dh_0 dh dx dy. \end{aligned} \tag{9}$$

If the maximum transmission power of the mobile users in the system is $P_t^{\max}$, and since it is required that the minimum receiving power is $P_r^{\min}$, for any mobile user its PLU must be less than a threshold, $K_S = 10\log_{10}\left(P_t^{\max}/P_r^{\min}\right)$, so that it can be served by the system. Thus, in order to maintain the N active mobile users assigned to each BS, ρ must be revised to ρ_{K_S} as

$$\rho_{K_S} = \frac{\rho}{F(K_S)}. \tag{10}$$

Correspondingly, the K_S-limited $F(K)$, denoted as $F_{K_S}(K)$, can be expressed as

$$F_{K_S}(K) = \frac{F(K)}{F(K_S)}. \tag{11}$$

III. The New Inter-Cell Interference Model

For the i^{th} mobile user assigned to the n^{th} BS, denoted as the (i,n) user, its reverse link signal-to-interference-plus-noise ratio (SINR) is given by the following expression [7]

$$\frac{E_b^{in}}{I_t^{in}} = \frac{P_{inn}/R}{(I_a^{inn}+I_e^{inn})/B_w + N_0F_N} \tag{12}$$

where P_{inn} is the average receiving power, R is the information bit rate and B_w is the spreading bandwidth of the mobile users, N_0 is the single-sided power spectral density of the thermal noise, and F_N is the noise figure of the BS receivers. Furthermore I_a^{inn} and I_e^{inn} are the intra-cell and the inter-cell interferences the (i,n) user suffers at the n^{th} BS, respectively. I_e^{inn} can be mathematically expressed as [8]

$$\begin{aligned}I_e^{inn} &= E\left[\sum_{j=1}^{N}\sum_{m=0,m\ne n}^{M-1} P_{jmn}\right]\\ &= E\left[\sum_{j=1}^{N}\sum_{m=0,m\ne n}^{M-1} \exp\{\beta(PL_{jmm}-PL_{jmn})\}P_{jmm}\right] \end{aligned} \tag{13}$$

where P_{jmn} is the receiving power of the (j,m) user at the n^{th} BS, PL_{jmn} and PL_{jmn} are the PL from the (j,m) user to the n^{th} and the m^{th} BSs, respectively, and $\beta = \ln 10/10$. Unfortunately, PL_{jmm} and PL_{jmn} are random variables whose probability density functions (pdfs) are very difficult to derive analytically. Consequently, instead of directly obtaining I_e^{inn} from (13), an alternative evaluation method will be proposed next.

In the past, the most widely accepted inter-cell interference model simplifying the calculation of I_e^{inn} has been proposed in [8] and [9]. However, this model can only be used to calculate the inter-cell interference of the systems with equal receiving power, e.g., for systems employing SUD. In [7] it was shown that for such systems, I_a^{inn} is given by

$$I_a^{inn} = \sum_{j=1,j\ne i}^{N} P_{jnn}. \tag{14}$$

Using (12)-(14), it is straightforward to show that in order to maintain the same SINR for all mobile users, i.e., $E_b^{in}/I_t^{in} = a$, $\forall i \in [1,N]$, and $\forall n \in [0, M-1]$, where a is a constant, all mobile users must have the same receiving power at their assigned BS. Equivalently stated, P_{inn} must satisfy the following condition

$$P_{inn} = P,\ \forall i \in [1,N],\ \forall n \in [0,M-1]. \tag{15}$$

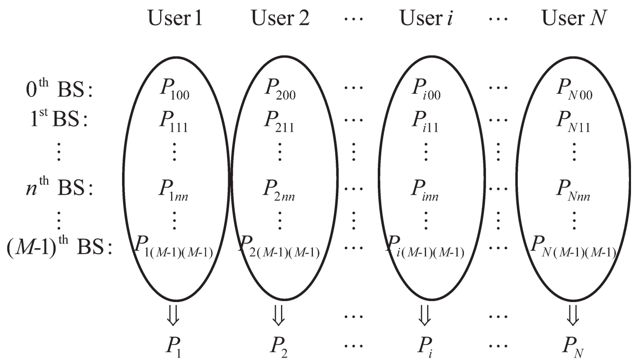

Fig. 2. Receiving power matrix for mobile users employing SIC.

Therefore, by using the inter-cell interfere model proposed in [8] and [9], I_e^{inn} is calculated as follows

$$I_e^{inn} = NR_eP \tag{16}$$

where

$$R_e = E\left[\sum_{j=1}^{N}\sum_{m=0,m\neq n}^{M-1} \exp\left\{\beta(PL_{jmm} - PL_{jmn})\right\}\right] \Big/ N. \tag{17}$$

In the above equation, R_e is the joint inter-cell interference factor, which is independent of P and N (due to the division by N), but depends upon the PL model considered by the system. The methodology for estimating R_e has been thoroughly presented in [8] and [9]. However, when SIC is employed this methodology cannot be used. Thus an alternative approach is necessary which will be presented next.

Let us consider that N mobile users assigned to the same BS are ranked and notated according to their PLU, i.e.

$$PL_{1nn} \leq PL_{2nn} \leq \ldots \leq PL_{inn} \leq \ldots \leq PL_{Nnn}, \quad \forall n \in [0, M-1]. \tag{18}$$

When SIC is employed, I_a^{inn} can be expressed as

$$I_a^{inn} = \sum_{j=1}^{i-1} \psi P_{jnn} + \sum_{j=i+1}^{N} P_{jnn} \tag{19}$$

where $\psi \in [0,1]$ is the interference cancellation factor indicating the portion of the remaining interference after each SIC step. From (19), it is clear that for each BS the intra-cell interferences of the N mobile users satisfy the following

$$I_a^{1nn} \geq I_a^{2nn} \geq \ldots \geq I_a^{inn} \geq \ldots \geq I_a^{Nnn}, \ \forall n \in [0, M-1]. \tag{20}$$

Using (12), (13) and (20), it is straightforward to show that when SIC is employed and in order to maintain the same SINR, the receiving powers of the N mobile users for each BS must satisfy the following condition

$$P_{1nn} \geq P_{2nn} \geq \ldots \geq P_{inn} \geq \ldots \geq P_{Nnn}, \ \forall n \in [0, M-1]. \tag{21}$$

Obviously, due to the existence of such controlled power disparities, I_e^{inn} can no longer be calculated from (16). However, noticing from (21) the characteristics of the controlled power disparity, it can be concluded that when SIC is employed, the receiving power of a mobile user has strong correlation with the rank of its PLU among the $PLUs$ of the N mobile users assigned to the same BS. Since the considered cellular CDMA system consists of M identical cells, it is reasonable to assume that, for the receiving power matrix shown in Fig. 2, the matrix elements within a single column have the same value, i.e.

$$P_{inn} = P_i, \ \forall i \in [1, N] \text{ and } \forall n \in [0, M-1]. \tag{22}$$

Based upon this assumption, the following inter-cell interference model is proposed

$$I_e^{inn} = \sum_{j=1}^{N} R_e^{jN} P_j, \tag{23}$$

where R_e^{jN} are the individual inter-cell interference factors for mobile users whose PLU has the j^{th} minimum value among all N mobile users assigned to the same BS. Using (22), (23) into (13), R_e^{jN} can be mathematically expressed as

$$R_e^{jN} = E\left[\sum_{m=0,m\neq n}^{M-1} \exp\left\{\beta(PL_{jmm} - PL_{jmn})\right\}\right]. \tag{24}$$

Clearly from the above equation, R_e^{jN} is independent of $\{P_j, j \in [1, N]\}$, but depends on j, N and the specifically used PL model.

By comparing (23) and (16), it is obvious that for the newly proposed inter-cell interference model the condition that all mobile users must have equal receiving power is no longer necessary. Thus, once the values of $\left\{R_e^{jN}, j \in [1, N]\right\}$ are obtained, the inter-cell interference of the systems employing SIC can be easily calculated from (23). Furthermore, if all mobile users have equal receiving power, P, using (17), (23), and (24), I_e^{inn} becomes

$$\begin{aligned} I_e^{inn} &= \sum_{j=1}^{N} R_e^{jN} P \\ &= P\sum_{j=1}^{N} E\left[\sum_{m=0,m\neq n}^{M-1} \exp\left\{\beta(PL_{jmm} - PL_{jmn})\right\}\right] \\ &= PE\left[\sum_{j=1}^{N}\sum_{m=0,m\neq n}^{M-1} \exp\left\{\beta(PL_{jmm} - PL_{jmn})\right\}\right] \\ &= NR_eP. \end{aligned} \tag{25}$$

The above equation clearly shows that the proposed inter-cell interference model is very general as it can be used to obtain I_e^{inn} not only for mobile users with controlled power disparity, but also for those with equal receiving power, as is the case with the model suggested in [8] and [9].

IV. Individual Inter-Cell Interference Factors

As it is very difficult to directly evaluate R_e^{jN} from (24), an alternative approach will be adopted. Firstly, it is noted that due to the symmetry of the system, R_e^{jN} can be evaluated by only considering the inter-cell interference to the 0^{th} BS (see Fig. 1). As S_0 is the SA of the 0^{th} BS, the mobile users

$$
\begin{aligned}
I_r^{S_0}(x,y) &= \sum_{m=1}^{N_C-1} E\left[\exp\left\{\beta(PL_m - PL_0)\right\}; PL_m \le PL_j, j \in [0, N_C-1], j \ne m; PL_m \le K \,|(x,y)\right] \\
&= \sum_{m=1}^{N_C-1} R_m^{\mu} E\left[\exp\left\{\beta b(h_m - h_0)\right\}; h_m \le \frac{K - M_m - ah}{b}; h_j \ge \frac{bh_m + M_m - M_j}{b}, j \in [0, N_C-1], j \ne m\right] \\
&= \frac{\exp\left(b^2\beta^2\sigma^2\right)}{2\pi\sigma^2} \sum_{m=1}^{N_C-1} R_m^{\mu} \int_{-\infty}^{+\infty} \exp\left(-\frac{h^2}{2\sigma^2}\right) \int_{-\infty}^{\frac{K-M_m-ah}{b}} \exp\left[-\frac{(h_m - b\beta\sigma^2)^2}{2\sigma^2}\right] Q\left(\frac{bh_m + M_m - M_0 + b^2\beta\sigma^2}{b\sigma}\right) \\
&\qquad \prod_{j=1, j\ne m}^{N_C-1} Q\left(\frac{bh_m + M_m - M_j}{b\sigma}\right) dh_m dh
\end{aligned} \tag{26}
$$

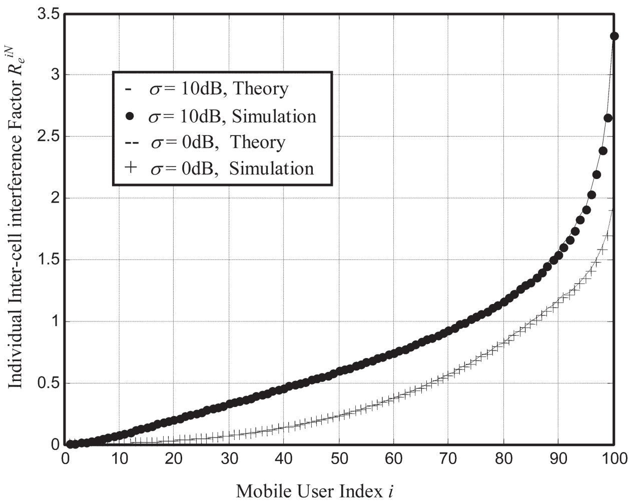

Fig. 3. Individual inter-cell interference factors with and without the effects of log-normal shadow fading.

located in areas other than S_0[2] cannot be assigned to the 0^{th} BS. Thus, the interference produced by all those mobile users is the inter-cell interference to the 0^{th} BS. On the contrary, the mobile users within S_0 may be assigned to the 0^{th} BS. Consequently, only the interference produced by the mobile users who are not assigned to the 0^{th} BS is the inter-cell interference to the 0^{th} BS. Due to this difference, the inter-cell interference originating from S_0 and that originating from $\overline{S}_0$ must be evaluated separately. The values of $\left\{R_e^{jN}, j \in [1, N]\right\}$ will be obtained by combining the evaluation results for these two regions.

A. Inter-Cell Interference Originating from S_0

For a mobile user located at $(x, y) \in S_0$ but not assigned to the 0^{th} BS and whose PLU satisfies that $PLU \le K$, using (5) and (7) its inter-cell interference to the 0^{th} BS, $I_r^{S_0}(x, y)$, can be mathematically expressed as (26), where $R_m^{\mu} = [r_m(x, y)/r_0(x, y)]^{\mu}$. From the above equation, the total inter-cell interference to the 0^{th} BS produced by all such mobile users can be obtained through the following double integral

$$
I_N^{S_0 - K_S}(K) = \iint_{S_0} I_r^{S_0}(x, y)\rho_{K_S} dxdy\,. \tag{27}
$$

Furthermore, the total inter-cell interference to the 0^{th} BS produced by all mobile users located at $(x, y) \in S_0$ but not assigned to the 0^{th} BS, and whose PLU satisfies that $PLU = K$, is given by

$$
\begin{aligned}
i_N^{S_0 - K_S}(K) &= \frac{dI_N^{S_0 - K_S}(K)}{dK} \\
&= \exp\left(b^2\beta^2\sigma^2\right) \iint_{S_0} \sum_{m=1}^{N_C-1} R_m^{\mu} \\
&\quad \int_{-\infty}^{+\infty} \frac{\exp\left(-h^2/2\sigma^2\right)}{\sqrt{2\pi}\sigma} \frac{\exp\left[-\frac{(K - M_m - ah - b^2\beta\sigma^2)^2}{2b^2\sigma^2}\right]}{\sqrt{2\pi}b\sigma} \\
&\quad Q\left(\frac{K - ah - M_0 + b^2\beta\sigma^2}{b\sigma}\right) \\
&\quad \prod_{j=1, j\ne m}^{N_C-1} Q\left(\frac{K - ah - M_j}{b\sigma}\right) \rho_{K_S} dhdxdy.
\end{aligned} \tag{28}
$$

B. Inter-Cell Interference Originating from $\bar{S}_0$

Similarly, for another mobile user who is located at $(x, y) \in \bar{S}_0$, if its PLU again satisfies the condition $PLU \le K$, using (5) and (7) the inter-cell interference produced by this mobile user to the 0^{th} BS, denoted as $I_r^{\bar{S}_0}(x, y)$, is given by (29), which is shown at the top of the next page.

Similarly to the previous case, the total inter-cell interference to the 0^{th} BS produced by all such mobile users, is given by

$$
I_N^{\bar{S}_0 - K_S}(K) = \iint_{\bar{S}_0} I_r^{\bar{S}_0}(x, y)\rho_{K_S} dxdy\,. \tag{30}
$$

Finally, the total inter-cell interference to the 0^{th} BS produced by all the mobile users, located within $\overline{S}_0$, and under the same

[2] Such areas will be denoted as $\overline{S}_0$.

$$
\begin{aligned}
I_r^{\bar{S}_0}(x,y) &= \sum_{m=1}^{N_C} E\left[\exp[\beta(PL_m - PL_0)]; PL_m \le PL_j, j \in [1, N_C], j \ne m; PL_m \le K \,|(x,y)\right] \\
&= \sum_{m=1}^{N_C} R_m^{\mu} E\left[\exp[\beta b(h_m - h_0)]; h_m \le \frac{K - M_m - ah}{b}; h_j \ge \frac{bh_m + M_m - M_j}{b}, j \in [1, N_C], j \ne m\right] \\
&= \exp\left(b^2\beta^2\sigma^2\right) \sum_{m=1}^{N_C} R_m^{\mu} \int_{-\infty}^{+\infty} \frac{\exp\left(-\frac{h^2}{2\sigma^2}\right)}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\frac{K-M_m-ah}{b}} \frac{\exp\left[-\frac{(h_m - b\beta\sigma^2)^2}{2\sigma^2}\right]}{\sqrt{2\pi}\sigma} \prod_{j=1, j\ne m}^{N_C} Q\left(\frac{bh_m + M_m - M_j}{b\sigma}\right) dh_m dh.
\end{aligned} \tag{29}
$$

condition $PLU = K$, can be obtained as

$$
\begin{aligned}
i_N^{\bar{S}_0 - K_S}(K) &= \frac{dI_N^{\bar{S}_0 - K_S}(K)}{dK} = \exp\left(b^2\beta^2\sigma^2\right) \\
&\iint_{\bar{S}_0} \sum_{m=1}^{N_C} R_m^{\mu} \int_{-\infty}^{+\infty} \frac{\exp\left[-(K - M_m - ah - b^2\beta\sigma^2)^2/2b^2\sigma^2\right]}{\sqrt{2\pi}b\sigma} \\
&\frac{\exp\left(-h^2/(2\sigma^2)\right)}{\sqrt{2\pi}\sigma} \prod_{j=1, j\ne m}^{N_C} Q\left(\frac{K - ah - M_j}{b\sigma}\right) \rho_{K_S} dh dx dy.
\end{aligned} \tag{31}
$$

C. Individual Inter-Cell Interference Factors

Using (11), the probability that a mobile user with $PLU = K$ has the i^{th} minimum PLU among the N mobile users assigned to the same BS can be found as

$$
Pr_{iN}^{K_S}(K) = C_{N-1}^{i-1} F_{K_S}^{i-1}(K)[1 - F_{K_S}(K)]^{N-i}. \tag{32}
$$

From the above equation and by employing (28) and (31), the individual inter-cell interference factor for all such mobile users can be derived as

$$
R_e^{iN}(K_S) = \int_{-\infty}^{K_S} \left[i_N^{S_0 - K_S}(K) + i_N^{\bar{S}_0 - K_S}(K)\right] Pr_{iN}^{K_S}(K) dK. \tag{33}
$$

D. Numerical Evaluations and Discussions

Using numerical techniques the values of $R_e^{iN}(K_S)$ have been obtained for the following typical parameters for the PL model of IMT-2000: $a = b = \sqrt{2}/2$, $N_C = 3$, and $\mu = 4$. Typical performance results are illustrated in Fig. 3[3] (for $\sigma =$ 0 and 10 dB) and Fig. 4 (for $\sigma = 4$, 8 and 12 dB), indicating mainly two important observations.

Firstly, it is noted that lognormal shadow fading significantly influences the inter-cell interference of cellular CDMA systems. For example, Fig. 3 clearly shows that when lognormal shadow fading is excluded from the PL model (i.e., σ = 0 dB), the values of $R_e^{iN}(K_S)$ are much smaller than those taking into account the effects of the lognormal shadow fading, e.g., σ = 10 dB. Furthermore, as illustrated in Fig. 4, as σ increases, so does $R_e^{iN}(K_S)$, especially of higher values of σ, e.g., σ = 12 dB. Thus, for an accurate estimation of the reverse link capacity it is essential that lognormal shadow fading be included in the PL model.

[3]As shown in this figure equivalent performance results obtained by means of computer simulations (see Section VI for details) are also included for verifications purposes.

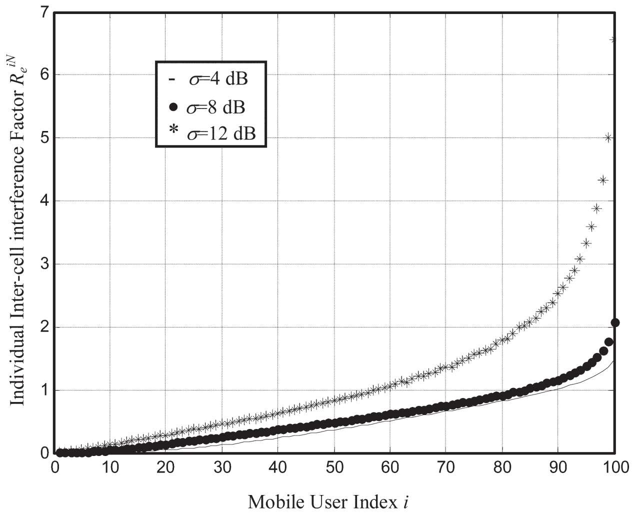

Fig. 4. Individual inter-cell interference factors for different values of σ.

Secondly, as it can be seen from Fig. 4, the individual inter-cell inference factors of mobile users with larger PLU are much higher as compared to mobile users with smaller PLU. Appropriately incorporating this observation into a detection algorithm, it is clear that SIC can significantly reduce inter-cell interference. Such inter-cell interference reduction will increase the reverse link capacity of cellular CDMA systems, especially for applications with high values of σ. Finally, it is of interest to mention that extensive numerical evaluations have allowed us to conclude that these two observations are valid independent of the actual values of the parameters of a, b, μ, N_C, N and K_S.

V. Reverse Link Capacity Analysis and Evaluation

Once $\left\{R_e^{jN}, j \in [1, N]\right\}$ have been obtained, I_e^{inn} can be evaluated using the inter-cell interference model given by (23). Hence, the reverse link capacity of cellular CDMA systems employing SIC can be precisely analyzed. For completeness and in order to clearly demonstrate the reverse link capacity improvements offered by SIC, both systems employing SUD and SIC will be considered.

For SIC, from (12), (19), and (23), the reverse link SINR for the (i, n) user can be mathematically expressed as

$$\tilde{A} = \begin{bmatrix} G_S - \alpha R_e^{1N}(K_S) & -\alpha[1+\alpha R_e^{2N}(K_S)] & \cdots & -\alpha[1+R_e^{(N-1)N}(K_S)] & -\alpha[1+R_e^{NN}(K_S)] \\ -\alpha[\psi + R_e^{1N}(K_S)] & G_S - \alpha R_e^{2N}(K_S) & \vdots & \vdots & \vdots \\ \vdots & -\alpha[\psi + R_e^{2N}(K_S)] & \ddots & -\alpha[1+R_e^{(N-1)N}(K_S)] & \vdots \\ \vdots & \vdots & \cdots & G_S - \alpha R_e^{(N-1)N}(K_S) & -\alpha[1+R_e^{NN}(K_S)] \\ -\alpha[\psi + \alpha R_e^{1N}(K_S)] & -\alpha[\psi + R_e^{2N}(K_S)] & \cdots & -\alpha[\psi + R_e^{(N-1)N}(K_S)] & G_S - \alpha R_e^{NN}(K_S) \end{bmatrix}$$

$$\frac{E_b^{in}}{I_t^{in}} = \frac{P_{inn}/R}{\left[\sum_{j=1}^{i-1} \psi P_{jnn} + \sum_{j=i+1}^{N} P_{jnn} + \sum_{j=1}^{N} R_e^{jN}(K_S) P_{jnn}\right] \Big/ B_w + N_0 F_N}. \tag{34}$$

Assuming perfect power control, i.e., $E_b^{in}/I_t^{in} = \alpha$, $\forall i \in [1, N]$, from (34), the following set of linear equations for $\{P_{inn}, i \in [1, N]\}$ are obtained

$$\tilde{A}\tilde{P}_{nn} = \tilde{B} \tag{35}$$

where
$\tilde{P}_{nn} = \left[P_{1nn}\ P_{2nn} \cdots P_{(N-1)nn}\ P_{Nnn}\right]^T$,
$\tilde{B} = [\alpha N_0 F_N B_w\ \alpha N_0 F_N B_w \cdots \alpha N_0 F_N B_w\ \alpha N_0 F_N B_w]^T$, and $\tilde{A}$ is given at the top of the next page, $G_S = B_w/R$ and ψ is the interference cancellation factor (see (19)). Using linear algebra it is straightforward to show that $\tilde{A}$ is a full rank matrix. Thus, by solving the set of linear equations in (35), $\{P_{inn}, i \in [1, N]\}$ are obtained as

$$P_{inn} = \gamma^{i-1} \frac{\alpha N_0 F B_w}{G_S - \alpha R_e^{1N}(K_S) - \alpha \sum_{j=2}^{N} \gamma^{j-1}[1 + R_e^{jN}(K_S)]} \triangleq P_{iN}^{SIC}(K_S) \tag{36}$$

where

$$\gamma = \frac{G_S + \alpha\psi}{G_S + \alpha}. \tag{37}$$

A. Single-User Detection (SUD)

When SUD is employed, no interference is cancelled after each mobile user is detected, i.e., $\psi = 1$. Thus, from (37), $\gamma = 1$, and hence using (36), $\{P_{inn}, i \in [1, N]\}$ is given by

$$P_{inn} = \frac{\alpha N_0 F B_w}{G_S - \alpha[\sum_{j=1}^{N} R_e^{jN}(K_S) + N - 1]} \triangleq P_N^{SUD},\ \forall i \in [1, N]. \tag{38}$$

From (38), it is clear that when SUD is employed, the N mobile users assigned to the same BS have the same receiving power, P_N^{SUD}.

If the maximum transmission power of the mobile users in the system is $P_t^{\max}$, in order to satisfy the condition that $E_b^{in}/I_t^{in} = \alpha$, $\forall i \in [1, N]$, it is clear from (38) that the *PLU* of the N mobile users assigned to the n^{th} BS, $\{PL_{inn}, i \in [1, N]\}$ must satisfy the following condition

$$PL_{inn} \le 10 \log_{10}(P_t^{\max}/P_N^{SUD}). \tag{39}$$

Therefore, for any mobile user, in order to be served by the cellular CDMA system under consideration, its *PLU* must be less than $10\log_{10}(P_t^{\max}/P_N^{SUD})$, i.e., $K_S^{SUD} = 10\log_{10}(P_t^{\max}/P_N^{SUD})$. Consequently, K_S^{SUD} must satisfy the following equation

$$K_S^{SUD} = 10 \log_{10} \frac{\{G_S - \alpha[\sum_{i=1}^{N} R_e^{iN}(K_S^{SUD}) + N - 1]\} P_t^{\max}}{\alpha N_0 F_N B_w}. \tag{40}$$

Once the values of K_S^{SUD} have been obtained from the above equation, using (9), the outage probability of the system employing SUD, $U^{SUD}(N)$, can be expressed as

$$U^{SUD}(N) = 1 - F(K_S^{SUD}). \tag{41}$$

B. Successive Interference Cancellation (SIC)

When SIC is employed, after each mobile user is detected its interference is either fully or partially cancelled, i.e., $0 \le \psi < 1$. Thus from (37), it is clear that $0 < \gamma < 1$, and hence, the receiving power of the N mobile users assigned to the same BS must satisfy the following inequalities

$$P_{1N}^{SIC}(K_S) > P_{2N}^{SIC}(K_S) > \ldots > P_{NN}^{SIC}(K_S). \tag{42}$$

It should be noted that the above equation confirms the analysis presented in Section III. There it was shown that when SIC is employed the receiving power of the mobile users assigned to the same BS has controlled disparity, and the mobile users with larger PLU require lower receiving power than those with smaller PLU.

In order to let $E_b^{in}/I_t^{in} = \alpha$, $\forall i \in [1, N]$, it can be seen from (36) that the *PLU* of the N mobile users assigned to the n^{th} cell must satisfy the following condition

$$PL_{inn} \le 10 \log_{10}[P_t^{\max}/P_{iN}^{SIC}(K_S)],\ \forall i \in [1, N]. \tag{43}$$

Since PL_{Nnn} takes the largest value among $\{PL_{inn}, i \in [1, N]\}$, it is clear from (43) that for any mobile user served by the cellular CDMA system its *PLU* must be less than $10\log_{10}[P_t^{\max}/P_{NN}^{SIC}(K_S)]$, i.e., $K_S^{SIC} =$

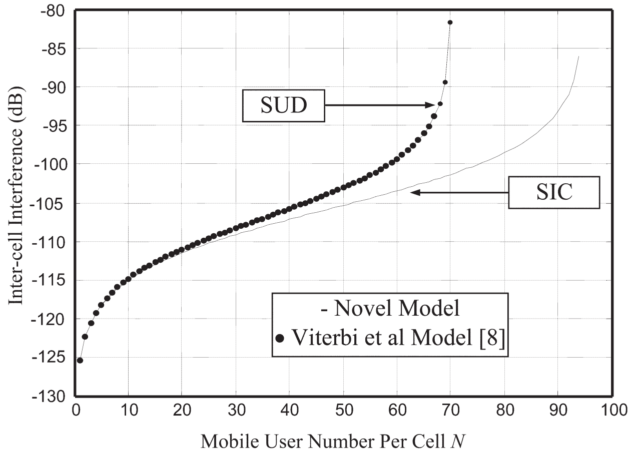

Fig. 5. Inter-cell interference comparison of SUD and SIC.

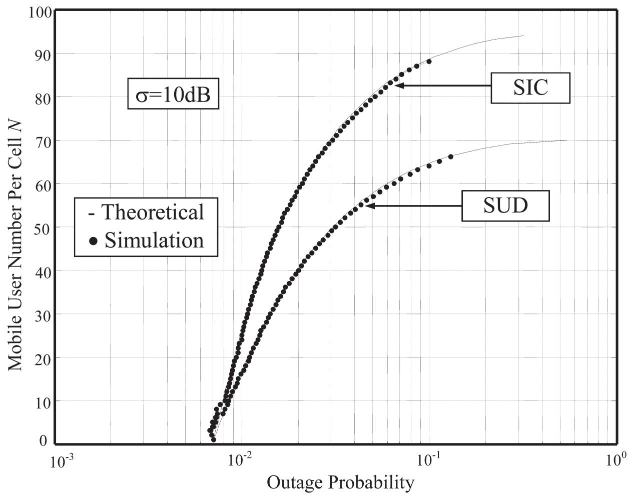

Fig. 6. Reverse link capacity comparison of SUD and SIC.

$10\log_{10}[P_t^{\max}/P_{NN}^{SIC}(K_S^{SIC})]$. Consequently K_S^{SIC} must satisfy the following equation

$$K_S^{SIC} = 10\log_{10}\left\{\frac{\left[G_S - \alpha R_e^{1N}(K_S^{SIC})\right]P_t^{\max}}{\alpha N_0 F_N B_w \gamma^{N-1}} - \frac{\alpha\sum_{j=2}^{N}\gamma^{j-1}[1+R_e^{jN}(K_S^{SIC})]P_t^{\max}}{\alpha N_0 F_N B_w \gamma^{N-1}}\right\}. \tag{44}$$

Similarly to the SUD case, once the values of K_S^{SIC} are obtained from (44), using (9) the outage probability of the system employing SIC, $U^{SIC}(N)$, is given by

$$U^{SIC}(N) = 1 - F(K_S^{SIC}). \tag{45}$$

C. Numerical Evaluations and Discussion

As a typical example the pedestrian mobile user model of a cdma2000 system has been considered. Using this model and, unless otherwise stated, the following numerical values for the different parameters have been selected [15]: $a = b = \sqrt{2}/2$, $\sigma = 10$ dB, $N_C = 3$, $\mu = 4$, $R = 9.6$ kbps, $G_S = 384$, $P_t^{\max} = 14$ dB and $\alpha = 5$ dB. Furthermore, the interference

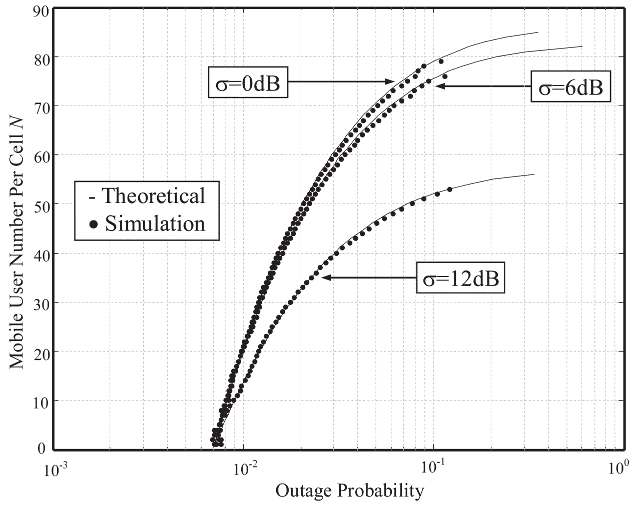

Fig. 7. Reverse link capacity under SUD for different values of σ.

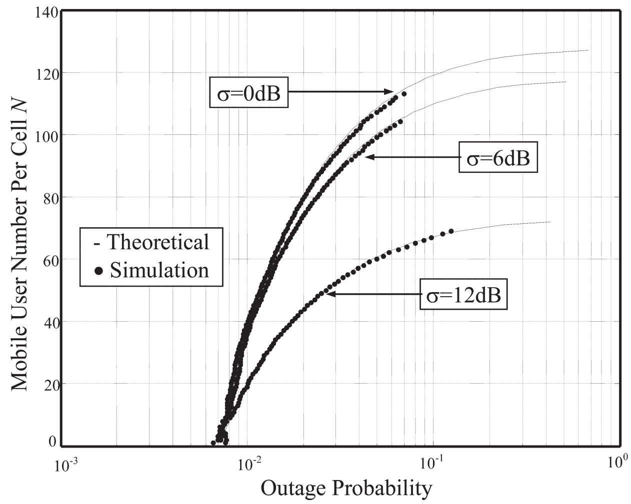

Fig. 8. Reverse link capacity under SIC for different values of σ.

cancellation factor, ψ, can be assumed to be of the form $\psi = 10^{-\alpha/10}$ [3]. By numerically evaluating (23), (36) and (38), the first set of evaluation results present in Fig. 5 the performance of I_e^{inn} versus N with SUD and SIC. From this figure it is clear that the inter-cell interference with SIC is much smaller than with SUD especially for higher values of N. For a fair comparison, we have also computed I_e^{inn} employing the model and method presented in [8] with SUD. As expected and in fact can be seen from Fig. 5, both models have identical performance with SUD. However, as previously argued, only our model can be used to estimate inter-cell interference under SIC. In order to demonstrate the capacity improvement SIC offers and the destructive effects of lognormal shadow fading, the values of $U^{SUD}(N)$ and $U^{SIC}(N)$ were evaluated with the same set of parameters except that σ took values in the range of $0 - 12$ dB. Due to the obvious difficulty in deriving closed-form solutions for K_S^{SUD} (see (40)) and for K_S^{SIC} (see (44)), instead, by employing recursive calculations numerical solutions were obtained. Since in general, the outage probability of a cellular CDMA system must be very small, e.g., less than 0.05,

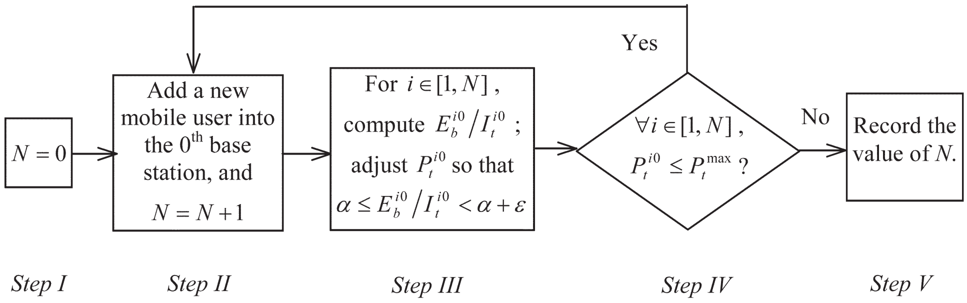

Fig. 9. Computer simulations model for outage probability evaluation.

K_S^{SUD} and K_S^{SIC} must take very large values. Since in the CDMA2000 standard the suggested path loss is 139.9 dB, using a margin of 20 dB, the initial values of K_S^{SUD} and K_S^{SIC} of our recursive calculations were chosen to be 160 dB.

Various performance evaluation results for $U^{SUD}(N)$ and $U^{SIC}(N)$ are presented in Figs. 5, 6, and 7. These results clearly indicate that for identical cellular CDMA systems, SIC can achieve much higher reverse link capacities as compared to SUD at any outage probability and for all values of σ. For example, as illustrated in Fig. 6, considering $\sigma = 10$ dB for when the outage probability is 0.01, SUD can only support 17 mobile users per cell, whereas SIC can support 26 mobile users per cell. For higher values of the outage probability, e.g., 0.3, SIC supports 93 mobile users per cell as compared to 69 mobile users SUD can support. Furthermore, as illustrated in Figs. 7 and 8, independent of detection techniques (i.e., SUD or SIC), lognormal shadow fading seriously increases inter-cell interference, and consequently decreases the capacity of cellular CDMA systems, especially for higher values of σ, e.g. $\sigma = 12$ dB.

VI. Computer Simulation Results and Discussion

In order to verify the correctness of the proposed theoretical analysis and the accuracy of the corresponding numerical evaluations, computer simulations were also performed to evaluate individual inter-cell interference factors and the reverse link capacities of the previously considered cellular CDMA systems.

A. Individual Inter-Cell Interference Factors

Following the cellular CDMA model presented in Section II, a cellular system with up to five tiers and 61 identical hexagonal cells was implemented in software. For this system, the individual inter-cell interference factors to the central BS, i.e., the 0^{th} BS, were evaluated by employing Monte Carlo simulation techniques, as follows. Firstly, mobile users uniformly distributed were added into the system one by one. If the minimum PL from the mobile user to the N_C nearest BSs is less than K_S, the mobile user is assigned to the BS with the minimum PL; otherwise, this mobile user is discarded. Secondly, if at least N mobile users were assigned to each of the $(M-1)$ BSs around the 0^{th} BS, these N mobile users were sorted and notated with ascending order starting from the minimum PL and ending with the maximum PL. Finally, for $i \in [1, N]$, the individual inter-cell interference factors, $R_e^{iN}(K_S)$, are calculated as follows

$$R_e^{iN}(K_S) = \sum_{n=1}^{M-1} \exp[\beta(PL_{inn} - PL_{in0})]. \quad (46)$$

By performing the above procedure sufficiently long (typically in the order of 10^4 times), the mean value of $R_e^{iN}(K_S)$ was obtained.

For a fair comparison in our computer simulations the same parameters as those in the numerical evaluations (see Section IV) have been used. Furthermore, since extensive simulation results have shown that inter-cell interference to the 0^{th} BS is mainly produced by the mobile users who are assigned to the first three tiers of BSs around the 0^{th} BS, $M = 37$ was selected. As illustrated in Fig. 3, the obtained computer simulation results perfectly confirm the numerical results obtained in Section IV thus validating the theoretical analysis.

B. SUD and SIC Reverse Link Capacity

Using the previously described computer simulation methodology, the outage probability of the mobile users assigned to the 0^{th} BS was evaluated in five-steps as shown in the flow chart presented in Fig. 9.

In *Step I*, the initial value of N is set to zero. In *Step II*, a new mobile user whose position follows the uniform distribution is created in the SA of the 0^{th} BS, S_0, and its PLs to the N_C nearest BSs are randomly produced according to the PL model presented in Section II. If the mobile user is not assigned to the 0^{th} BS, it is discarded, and another new mobile user is created. This procedure is repeated until the newly created mobile user is assigned to the 0^{th} BS, and then we set $N = N + 1$.

In *Step III*, first, by using (34) the SINR of the N mobile user assigned to the 0^{th} BS are obtained as

$$\frac{E_b^{i0}}{I_t^{i0}} = \frac{P_{i00}/R}{\left[\sum\limits_{j=1, j\neq i}^{N} P_{j00} + \sum\limits_{j=1}^{N} R_e^{jN}(K_S) P_{j00}\right] \Big/ B_w + N_0 F_N} \quad (47)$$

and

$$\frac{E_b^{i0}}{I_t^{i0}} = \frac{P_{i00}/R}{\left[\sum\limits_{j=1}^{i-1} \psi P_{j00} + \sum\limits_{j=i+1}^{N} P_{j00} + \sum\limits_{j=1}^{N} R_e^{jN}(K_S) P_{j00}\right] \Big/ B_w + N_0 F_N} \quad (48)$$

for SUD and SIC respectively. Afterwards, the transmission powers of the N mobile users assigned to the 0^{th} BS, $\{P_t^{i0}, i \in [1, N]\}$, are adjusted iteratively until the following condition is satisfied

$$\alpha \leq E_b^{i0}/I_t^{i0} < \alpha + \varepsilon, \ \forall i \in [1, N] \tag{49}$$

where ε is a small positive constant, e.g., $\varepsilon = 0.01$ dB.

In *Step IV*, the values of $\{P_t^{i0}, i \in [1, N]\}$ are checked. If all of them are less than $P_t^{\max}$, the simulation goes back to *Step II* so that a new mobile user is added to the 0^{th} BS. However, if any of these is larger than $P_t^{\max}$, this means that even when the mobile user has reached its maximum transmission power, $P_t^{\max}$, its SINR still cannot meet the system requirement. Thus, an outage event occurs, and the simulation goes forward to *Step V*.

In *Step V*, the value of N is recorded, and this round of simulation is implemented.

By performing the above five-step simulation sufficiently long, e.g., more than 10^4 times, the pdf for the outage events, denoted as $u_F(N)$ can be obtained. This pdf depicts the relation between N and the probability that among the N mobile users assigned to the 0^{th} cell, at least one mobile user fails to meet the SINR requirement. Hence, since these mobile users are independent from each other, the outage probability of the system is

$$U(N) = 1 - \sqrt[N]{1 - \sum_{i=1}^{N} u_F(i)}. \tag{50}$$

For a fair comparison, in our computer simulation we have used the same parameters as those in the numerical evaluations (see Section V). Furthermore, ε was set to 0.01 dB, which is sufficiently small to represent an almost perfect power control. In order to compare with the numerical results, the outage probabilities obtained from the computer simulation are also depicted in Figs. 5, 6 and 7. Clearly, the obtained computer simulation results confirm the numerical evaluation results. Hence, the accuracy of the theoretical analysis represented in Section V has been validated.

VII. Conclusions

A new approach for the analysis of the reverse link capacity of cellular CDMA systems with controlled power disparities has been presented. Based upon an accurate model of the inter-cell interference of such systems, a theoretical analysis for estimating the reverse link capacity of cellular CDMA systems has been developed. Theoretical and computer simulated performance evaluations have shown that, as compared to SUD, SIC provides significant capacity improvements for cellular CDMA systems operating in realistic controlled power disparities environments.

Acknowledgments

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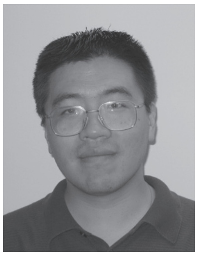

Hong Nie (S'00-M'04) received the Bachelor degree in Electronic Engineering in 1993 and the M. Eng. degree with specialization in wireless communication in 1995 from the Tsinghua University, China, and the Ph.D. degree with specialization in wireless communications from the University of British Columbia (UBC), Canada in 2004.

He is currently an instructor at Engineering Department of the Cape Breton University, Canada, where besides teaching various electronic courses, he has helped to establish the Wireless System Lab performing research in Petroleum Applications of Wireless Systems with grants from Canadian Foundation for Innovation, Natural Sciences and Engineering Research Council of Canada, and Atlantic Innovation Fund. Before Dr. Nie began his Ph.D. study at UBC, he has accumulated 3 years of industrial (hands-on and managerial) experience at Beijing Shannon Information Technology Ltd. and Multi-Tech Systems USA, Inc., Beijing Office, where he was working in the areas of wireless and data communications.

Dr. Nie's current research interests include advanced wireless transceiver architectures for sensors in petroleum applications, ultra wide-band techniques for wireless sensor transceivers, software defined radio & related digital signal processing techniques, inter-cell interference and capacity analysis of cellular CDMA systems, multi-user detection and macrodiversity techniques, channel coding & digital modulation techniques for mobile communications, OFDM transmission techniques, adaptive antenna array and multi-input multi-output systems.

P. Takis Mathiopoulos (SM'94) is currently Director of Research at the Institute for Space Applications and Remote Sensing (ISARS) of the National Observatory of Athens (NOA), where is has established the Wireless Communications Research Group. As ISARS' Director he has lead the Institute to a significant expansion, R&D growth and international scientific recognition. For these achievements, ISARS has been selected as one of the national Centers of Excellence for the years 2006-2008. Before joining ISARS, he worked in the early 80's for several years at Raytheon Canada Ltd in the areas of air-navigational and satellite communications. In the late 80's he joined the Department of Electrical and Computer Engineering (ECE) of the University of British Columbia (UBC), where he was a faculty member for 14 years last holding the rank of Full Professor. Maintaining his ties with academia, he is an adjunct Professor of ECE at UBC and also is teaching part-time at the Department of Informatics and Telecommunications, University of Athens. Over the years, Prof. Mathiopoulos has supervised university and industry based R&D groups and has successfully acted as technical manager for R&D Canadian, European and Greek projects.

He has supervised more than 30 graduate students in Canada and Greece and has been the PI for more than 35 R&D projects. He has published close to 150 papers in journals and international conference proceedings and is on the Editorial board of many scientific journals, including the *IEEE Transactions on Communications*. He has regularly acted as a consultant for several governmental and private organizations, including the European Commission. Prof. Mathiopoulos has delivered numerous invited presentations, including plenary lectures, and has taught many short courses all over the world.

George K. Karagiannidis (M'96-SM'04) was born in Pithagorion, Samos Island, Greece. He received his university degree in 1987 and his PhD degree in 1999, both in Electrical Engineering, from the University of Patras, Patras, Greece. From 2000 to 2004 he was Researcher at the Institute for Space Applications & Remote Sensing, National Observatory of Athens, Greece. In June 2004, he joined the faculty of Aristotle University of Thessaloniki, Greece where he is currently an Assistant Professor at the Electrical & Computer Engineering Department.

His major research interests include Wireless Communications Theory, Digital Communications over Fading Channels, Satellite Communications, Mobile Radio Systems and Free-Space Optical Communications. Dr. Karagiannidis has published and presented more than 70 technical papers in scientific journals and international conferences, he is co-author in 3 chapters in books and also co-author in a Greek Edition Book on Mobile Communications.

He is member of the Editorial Boards of IEEE COMMUNICATIONS LETTERS and EURASIP Journal on Wireless Communications and Networking.