Performance of Reverse Link CDMA in a Multi-cell Environment with Moving Cells*

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Abstract

We present the bit error performance and capacity of the reverse link of a DS-CDMA cellular system, taking into account the effect of power-controlled interfering users from other cells. A convolutionally encoded, BPSK modulated, waveform is considered. The channel is assumed to undergo flat Rayleigh fading, which is typical of narrowband CDMA systems. All the mobile users are power-controlled by their assigned base stations. A cellular CDMA system with 25 cells in a square grid layout is simulated, and the performance in the center cell surrounded by 2-tiers of interfering cells is estimated. The effect of power control is accounted for by assuming the power control error to be log-normally distributed. We present the performance results when the base station of interest moves relative to other fixed base stations, resulting in overlapping cells, a situation possible in a battlefield environment where the base stations could be mounted on jeeps, tanks, UAVs, etc.

1 Introduction

The rather well-known advantages of jamming resistance, low probability of intercept, simple frequency coordination, multiple access, and ability to combat multipath make spread spectrum techniques combined with cellular communications architecture a natural choice for both commercial and battlefield wireless communications [1],[2],[3]. In this paper, we consider a direct sequence code division multiple access (DS-CDMA) cellular system employing convolutionally encoded BPSK modulation. The base-to-mobile link (forward link) and the mobile-to-base link (reverse link) operate on different frequency bands. The capacity of the reverse link in a multi-cell environment has been investigated by many authors [2],[4],[5],[6]. Most of these studies, for analytical simplicity, assume that a mobile talks to a base station which is nearest to it, and further, that the base stations do not move.

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In this paper, we study the reverse link performance in a multi-cell environment adopting two different base station assignment models, and compare their relative performances. The first model is based on a minimum distance criterion (*distance model*), and the second on a maximum received power criterion (*power model*). Adaptive power control is essential to counteract the effects of the near-far problem and shadowing, so as to ensure an average equal performance to all the users in the system. We allow all the mobiles to be power-controlled by their assigned base stations. The power control error (PCE) resulting due to imperfect power control is assumed to have a log-normal distribution, and the degradation of the reverse link capacity as a function of the standard deviation of the PCE is evaluated.

Dynamic base station mobility, in addition to user mobility, is a key issue in hostile battlefield environments, where the base stations could be mounted on moving platforms (e.g., jeeps, tanks, UAVs) and can move along with the soldiers as a cell [7]. We capture this scenario by allowing the cell-of-interest to move with respect to two tiers of interfering cells, and estimate the performance at the moving cell. In Section II, the system model, including cell layout, channel characteristics, and base station assignment models, is described. In Section III, the capacity estimation methodology is described. Section IV provides the results and discussions, and Section V presents the conclusions.

2 System Model

We consider a 25-cell square grid topology DS-CDMA cellular system with base stations $\{B_1, B_2, ..., B_{25}\}$ as shown in Figure 1. We are interested in the performance at the test cell with B_{12} as its base station. This test cell is surrounded

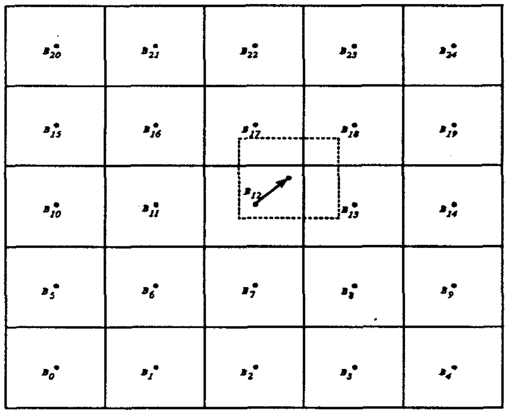

Figure 1: 25-cell square grid layout.

by two tiers of interfering cells. Tier-I has 8 interfering cells and tier-II has 16 interfering cells. Asynchronous mobile users are assumed to be randomly located in the system with a uniform density of K users-per-cell-area. Each user communicates with its base station on the reverse link using coherent BPSK modulation and direct sequence spreading. The spreading sequences have a common chip rate of $\frac{1}{T_c}$, where $T_c = \frac{T_b}{N_c}$. T_b and T_c are the bit and chip durations, repectively, and N_c is the processing gain.

We consider the channel relevant to a narrowband CDMA system, which is modelled by flat Rayleigh fading (i.e., the coherence bandwidth of the channel is assumed to be larger than the bandwidth of the signal) and shadowing. The factors that affect the received signal power are the distance and shadow losses. We adopt a standard distance loss model, namely, received power is inversely proportional to the distance raised to the power ν, where the propagation exponent ν varies in the range 2 to 5.5 depending on the environment. Apart from the attenuation due to distance, the signal also experiences loss due to shadowing which is caused by blockage (e.g., buildings, hills, foliage, etc). It has been shown through measurements that shadow loss has a log-normal distribution with standard deviation σ_s in the range 4 to 12 dB [8]. Thus, the received signal power is proportional to the $10^{(\zeta/10)}d^{-\nu}$, where d is the distance between the mobile and the base, and ζ is Gaussian random variable with zero mean and standard deviation σ_s dB.

Each mobile user's transmission on the reverse link is power controlled by its assigned base station. Due to adaptive power control, the signals from all in-cell users arrive at the base station with nominally equal power (except for the Rayleigh fading factor which represents the residual fading that varies too rapidly to be tracked out by the adaptive power control). The interfering signals from the out-of-cell users are compensated for distance and shadow losses to their own assigned base stations. Thus, the interference due to an out-of-cell user (assigned to base station B_m), at the desired user's base station B_0, is proportional to two factors, namely, a) attenuation caused by distance and shadowing to the desired user's base station B_0, and b) the effect of power control to compensate for the attenuation to the base station of the out-of-cell interferer B_m. That is,

$$I(d_0, d_m) \propto \left(\frac{10^{(\zeta_0/10)}}{d_0{}^{\nu}}\right)\left(\frac{d_m{}^{\nu}}{10^{(\zeta_m/10)}}\right) \qquad (1)$$

where d_m, d_0 are the distances of the out-of-cell interfering user to its own base station B_m, and the desired user's base station B_0, respectively. The variables ζ_m and ζ_0 are shadow parameters which are assumed to be independent, Gaussian random variables with zero means and equal standard deviations of σ_s dB.

Base Station Assignment

We consider two different models for base station assignment, *viz.*, 1) distance model, and 2) power model.

Distance model

In model 1, a mobile user is assigned to the base station B_x to which the mobile-to-base *distance is minimized*, i.e., x is the base station index for which

$$d_x = \min\{d_y\}, \qquad y \in \{0, 1, 2, ..., 24\}.$$

This model is used in [7] for analytical simplicity. In reality, due to fading and shadowing, the base station from which a mobile user receives the maximum power need not be the closest one.

Power model

Model 2 considers both distance and shadow losses for the base allocation. Here, a mobile user is assigned to a base station B_x for which the base-to-mobile *received power is maximized*, i.e., x is the base station index for which

$$d_x{}^{-\nu}10^{(\zeta_x/10)} = \max\left\{d_y{}^{-\nu}10^{(\zeta_y/10)}\right\} \qquad y \in \{0, 1, 2, ..., 24\}.$$

In addition to the above two models, we also consider an approximation to the power model, used in [2].

The received signal at the test base station B_{12} is given by

$$r(t) = \sum_{k=1}^{25K} A\lambda_k\alpha_k\gamma_k b_k(t-\tau_k)c_k(t-\tau_k)\cos(\omega_o t + \phi_k) + n_w(t), \qquad (2)$$

where

$$\gamma_k = \begin{cases} 1 & \text{if } k = \text{in-cell user} \\ \left(\frac{d_{m_k}}{d_{12_k}}\right)^{\nu/2} 10^{((\zeta_{12_k}-\zeta_{m_k})/20} & \text{if } k = \text{other-cell user.} \end{cases}$$

In (2), $\{\tau_k\}$ represents the random delays which are independent and uniformly distributed in $[0, T_b]$, and $\{\phi_k\}$, where $\phi_k = \theta_k - \omega_o\tau_k$, represents the independent identically distributed random carrier phases uniformly distributed in $[0, 2\pi]$. The thermal noise term, $n_w(t)$, is additive white Gaussian with two-sided power spectral density $\eta_o/2$, α_k is a

Rayleigh random variable representing fading due to multipath, and λ_k is the power control error which is a random variable log-normally distributed with standard deviation σ_e dB (i.e., $\lambda_k = 10^{(\frac{X}{20})}$, where the variable X follows a normal distribution). At the receiver, the signal is coherently despread and demodulated.

3 Capacity Estimation

A quasi-analytic approach is adopted to estimate the bit error performance, and thus the capacity on the reverse link of the DS-CDMA system. We first estimate the uncoded bit error performance of the system at different system parameter settings through large scale simulations. We assume *perfect interleaving*, and evaluate an upper bound on the coded bit error performance of the system using convolutional codes with hard decision Viterbi decoding. For convolutional codes with hard decision Viterbi decoding, the BER transfer characteristic can be upper-bounded by the well known transfer function bound

$$p_o < \sum_{i=x_f}^{\infty} \beta_i P(i), \quad (3)$$

where x_f is the free distance of the code, and $\{\beta_i\}$ are the coefficients in the expansion of the derivative of $T(D,N)$, the transfer function (or generating function) of the code, evaluated at $N = 1$ [9]. $P(i)$ is the probability of selecting an incorrect path, which can be bounded by the expression

$$P(i) < [4p(1-p)]^{i/2}, \quad (4)$$

where p is the uncoded BER. From the coded bit error performance, we then estimate the system capacity, which is defined as the number of simultaneous users that can be supported while maintaining an acceptable BER performance needed by the specific application (e.g., 10^{-3} for voice).

Simulation

The reverse link of the 25-cell DS-CDMA cellular system model described above has been simulated, with and without the test-cell motion. When there is no cell motion, all the base stations are kept static. New, random, user location and shadow fading processes are generated in each simulation run and the average bit error performance at the test cell is computed. In the moving-cell case, a quasi-static model is assumed. That is, the base station B_{12} and the mobiles in the test cell area are moved into an adjacent cell's boundaries, and the BER is computed with the test-cell stationary at different positions in its range of motion. Note that the cell geometries become distorted and take random shapes when one accounts for base station movement.

A set of CDMA simulation tools developed in C language has been used to synthesize the simulation program.

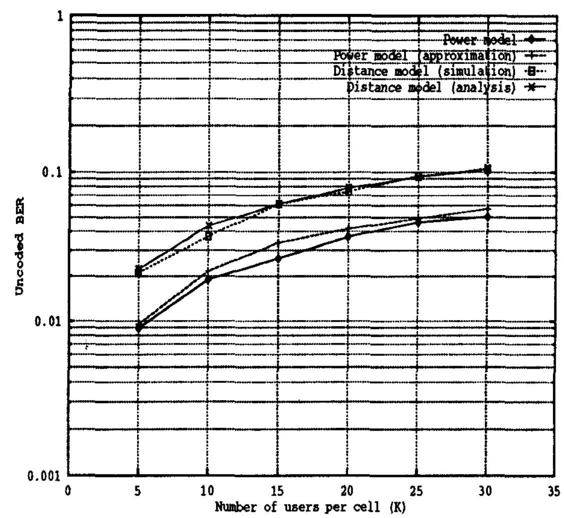

Figure 2: Uncoded BER *vs* number of mobile users per cell (K) for different base allocation models. Static base stations. No AWGN. $\sigma_s = 6$ dB. $\sigma_e = 0$ dB.

Random binary sequences of length 127 are used as the spreading codes for different users. All the users transmit asynchronously with different time delays τ_k with respect to the user-of-interest associated with the test base station B_{12}, such that τ_k is chosen randomly in the set $\{0, T_s, 2T_s, ..., (N_cJ-1)T_s\}$, where T_s is the sampling interval, and J is the number of samples per chip. A sampling rate corresponding to 4 samples per chip is employed. Consistent with the previous studies [2],[7], the propagation exponent ν is taken to be 4 in all the simulations. System parameters such as the number of mobile users per cell (K), the shadow loss parameter (σ_s), the standard deviation of the power control error (σ_e), and the distance and direction of the test-cell motion, are varied in the simulation program to study their affect on the system performance.

4 Results and Discussion

First, we simulate the static base stations scenario to evaluate and compare the uncoded bit error performance of the system under the two different base allocation models. The simulation results with model 1 are compared with the analytical results of [7]. Figure 2 shows the simulated bit error rate performance of the reverse link as a function of number of mobile users per cell (K) when there is no AWGN, no power control error (i.e., $\sigma_e = 0$ dB), and the shadow parameter σ_s is 6 dB. The analytical performance, as per [7], for the 25-cell square grid layout is also plotted. The analytical and simulation results for the distance model (model 1) of base allocation are in close agreement with each other. In addition, use of base allocation model 2 (power model) show

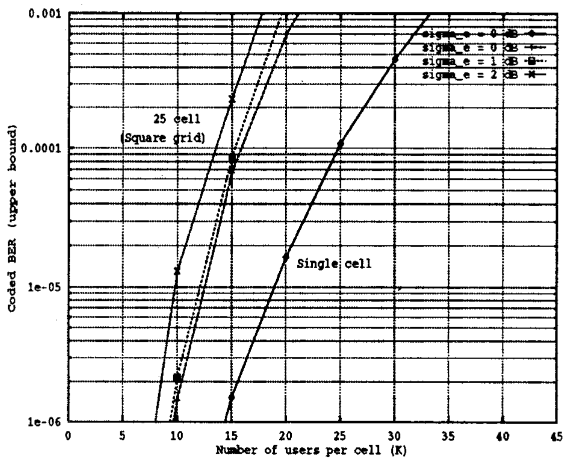

Figure 3: Upper bound of the coded BER *vs* number of mobile users per cell (K). Static base stations. No AWGN. $\sigma_s = 8$ dB. *a*) Single cell case; $\sigma_e = 0$ dB. *b*) 25-cell case; $\sigma_e = 0$ dB, 1dB, 2 dB.

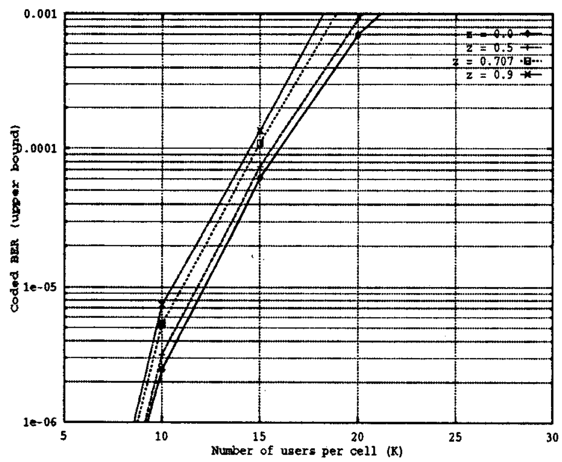

Figure 4: Upper bound of the coded BER *vs* number of mobile users per cell (K). Test cell moving in the *horizontal* direction. Distance moved, z = 0.0, 0.5, 0.707, 0.9. No AWGN. $\sigma_s = 8$ dB. $\sigma_e = 0$ dB.

better BER performance compared to model 1. This is because an other-cell user, though nearest to its assigned base station, may have a small shadow loss to the base station-of-interest, causing severe multiple access interference. The interference analysis presented in [2] uses an approximation to the power model of base allocation to simplify the analysis. The BER performance using this approximation (*viz.*, distance model with additional power constraint) is also plotted and compared. The approximation is found to predict better performance than the distance model. However, it provides an under-estimate of the performance compared to the pure power model, as seen from Figure 2. Since the power model is closer to reality, and offers better performance than other models, we will use this model for the rest of the simulations and discussion.

Next, we examine the effect of multiple access interference from adjacent cells, in conjunction with power control error, on the system capacity, again, for the static cell scenario. In Figure 3, we plot the upper bound of the coded BER as a function of the number of users-per-cell, both for a single cell system and the 25-cell square grid layout. A rate-1/3 convolutional code of constraint length 9 with hard decision Viterbi decoding is used. The $\{\beta_i\}$ coefficients in Equation 3 are taken from [10]. It is seen that, when $\sigma_e = 0$ dB, a single cell system (without any adjacent cell interference) can support 33 simultaneous voice circuits, meeting a BER requirement of 10^{-3}. However, for a 25-cell system, the number of simultaneous voice calls reduces to 21, amounting to a 36 % reduction in capacity. This result is in consistent with the results reported in [2]. Figure 3 also shows the BER curves for a 25-cell system when the standard deviation of the PCE, σ_e, is both 1 dB and 2 dB. It is found that the capacity reduces to 19 users (around 10 % degradation compared to the no PCE case) when $\sigma_e = 1$ dB, and further degrades to 17 users (around 19 % degradation compared to the no PCE case) when $\sigma_e = 2$ dB.

Finally, we simulate a moving cell scenario and estimate the capacity of the moving cell as a function of the degree of cell overlap and the direction of motion. Let z be the distance moved by the test-cell normalized with respect to the cell width. Because of the symmetry involved in the square grid layout, we evaluate the performance for the cases when the test-cell moves in both horizontal and diagonal directions. Figure 4 shows the BER performance at the test cell for various degrees of cell overlap in the horizontal direction. The various values of z considered are 0.0, 0.5, 0.707, and 0.9. Note that the value $z = 0.0$ corresponds to the static base station scenario, and $z = 0.5$ corresponds to the test base station being at the midpoint between the static location of B_{12} and that of B_{13}. It is seen that even when the test-cell moves close to B_{13} (e.g., $z = 0.9$), the capacity degradation compared to the static base stations scenario is only around 15 %, when $\sigma_e = 0$ dB. This result is in contrast to the results reported in [7], where the capacity was shown to degrade drastically when the fractional cell overlap increases beyond a certain point. This discrepancy is attributed to the distance model of base allocation used in [7], which gave pessimistic performance estimates.

Figure 5 gives the BER performance at the test-cell when it moves in a diagonal direction towards B_{18} between B_{13} and B_{17}. Here, the value $z = 0.707$ corresponds to the test base station being moved to the intersection of the cell boundaries of B_{13}, B_{17}, and B_{18}. The values considered for shadow loss and PCE parameters are $\sigma_s = 8$ dB and $\sigma_e = 0$ dB, respectively. Note that again, a gradual degradation in capacity up to 15% is observed. Figure 6 illustrates the variation in

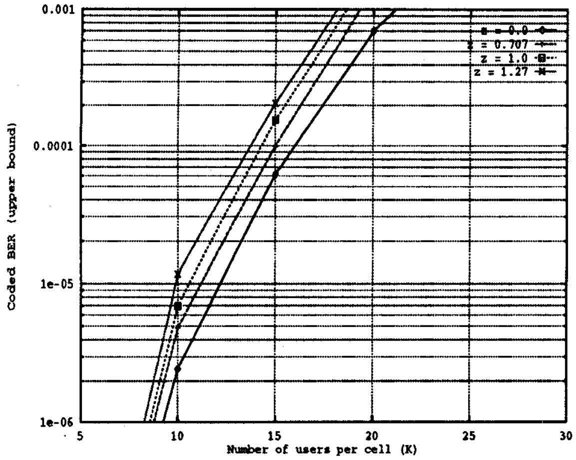

Figure 5: Upper bound of the coded BER *vs* number of mobile users per cell (K). Test cell moving in the *diagonal* direction. Distance moved, z = 0.0, 0.707, 1.0, 1.27. No AWGN. $\sigma_s = 8$ dB. $\sigma_e = 0$ dB.

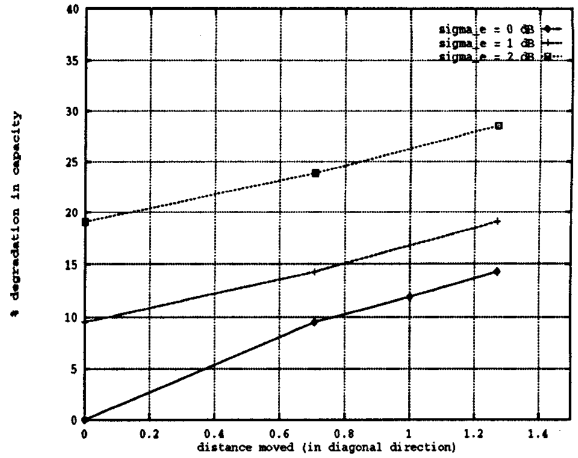

Figure 6: % degradation in capacity as a function of distance moved, z (in diagonal direction), and the standard deviation of PCE. No AWGN. $\sigma_s = 8$ dB. $\sigma_e = 0$ dB, 1 dB, 2 dB.

the percentage degradation in capacity as a function of the diagonal distance moved; the curves are parameterized by σ_e. As the test-cell moves too close to B_{18}, the capacity is found to degrade up to around 20 % when σ_e is 1 dB, and worsens to 30 % when σ_e is 2 dB.

5 Conclusions

We presented the reverse link capacity of a DS-CDMA system in a multi-cell environment with moving cells, which is a likely scenario in emergency as well as battlefield communications. Two different base allocation models were considered. Under the static base station scenario, using the received power criterion for base allocation, the reverse link capacity estimates in a 25-cell square grid cell layout was found to be worse by 36 % compared to a single cell system devoid of adjacent cell interference. The power control error was found to degrade the capacity by 19 % when the standard deviation of PCE was 2 dB. Capacity degradation up to 30 % was observed when the test cell moves very close to the adjacent cells. Also, the degradation as a function of cell overlap was found to be much more gradual than what was predicted in [7], which used the distance criterion for base station assignment.

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