Open-Loop Power Control Performance in DS-CDMA Networks with Frequency Selective Fading and Non-Stationary Base Stations

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In this paper, we study the performance of a simple and easy-to-implement distributed power control strategy applicable to direct sequence code division multiple access (DS-CDMA) networks. The scheme makes use of the received power measurements made on the forward link at individual mobile units to control the transmit powers on their reverse links. The algorithm, which effectively compensates for the slowly varying distance and shadow losses (due to their high correlation on both forward and reverse links), attempts to minimize the effect of fast multipath fading by averaging it out. We adopt a quasi-analytic approach to estimate the reverse link capacity performance of an open-loop power control scheme in both a single cell and a multi-cell environment, and we do this both for a fixed base station as well as a moving base station scenario. Non-stationary base stations are typical in tactical and emergency communications scenarios where the base stations could be mounted on moving platforms (e.g., tanks, jeeps, unmanned airborne vehicles). We estimate the capacity degradation, when base stations move relative to other cells, as a function of the amount of cell overlap and the standard deviation of the power control error. We also provide a comparison of the performance of the open-loop power control strategy with that of a closed-loop power control strategy.

Keywords: open-loop power control, DS-CDMA, frequency selective fading, non-stationary base stations.

1 – Introduction

Transmitter power control remains to be a crucial issue in cellular direct sequence code division multiple access (DS-CDMA) networks, as the capacity maximiza-

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tion and fair allocation of resources among different users largely depend on the effectiveness of the power control scheme employed [1], [2]. An adaptive power control (APC) scheme is desirable to combat the effects of fading, shadowing and distance losses. Such a scheme attempts to maintain a constant average performance among the users, minimize the required transmit power at each user terminal, and reduce the multiple-access interference effect. There are two forms of APC, *viz.*, open-loop and closed-loop APC. In closed-loop implementations, the reverse link (mobile-to-base station link) channel state is estimated by the base station, which then transmits this information back to the mobile on the forward link (base station-to-mobile link) for use in controlling the mobile's transmit power [3], [4]. In a terrestrial cellular environment, such a scheme is feasible under most conditions; however, even with low earth orbit (LEO) satellites, the round trip propagation delay is about 10ms for a 400 nautical mile satellite and up to 60ms for 800 nautical mile satellites at lower elevation angles [5]. Because closed-loop schemes are sensitive to this round trip delay, their use is typically not effective in a land mobile satellite system, since such a system suffers from rapid multipath fading. That is, due to the large round trip propagation delay, the fades occur too rapidly for the closed-loop APC to track. An alternate, and simpler form of power control is an open-loop system [6]. In such a scheme, the channel state on the forward link is estimated by the mobile user, and this estimate is used as a measure of the channel state on the reverse link. This technique is ideal if the forward and reverse links are perfectly correlated. However, due to multipath fading, this is not, in general, true. Nevertheless, open-loop APC can compensate for large scale variations such as shadowing, and it provides a fast, inexpensive method to equalize average received power at the base station. An open-loop APC algorithm should therefore attempt to minimize the effect of the multipath fading component by averaging it out. This results in a randomly varying power control error (PCE) that causes performance degradation. The resulting distribution of the open-loop power control error on a frequency selective Rayleigh fading channel is shown to have an approximately log-normal distribution with the standard deviation typically varying in the range 1 to 4 dB depending on the measurement interval, vehicle velocity, and the number of RAKE receiver taps [7].

In this paper, using a quasi-analytic approach, we estimate the reverse link capacity of the open-loop power control (OLPC) scheme in both a single cell as well as a multi-cell environment. Our key focus here is to predict the degradation of the reverse link capacity due to both the open-loop power control error and the presence of non-stationary base stations in the system. Non-stationary base stations become necessary to provide an effective communications infrastructure in tactical and emergency communications environments, where base stations could be mounted on moving platforms like jeeps, tanks, unmanned airborne vehicles (UAV), etc., which can move along with the users as a cell. Thus, dynamic base station mobility, in addition to the user mobility, becomes a key issue which affects performance. The reverse link capacity in a multi-cell environment has been investigated by many authors [1], [8], [9]. 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. The first attempt to analyze the reverse link performance in a moving base station scenario was reported in [10], where the mobile-to-base distance was the only criterion considered for the base station assignment to individual mobiles. In fact, the nearest base station need not always be the best choice because of the losses due to fading and shadowing. It is more appropriate to consider the average received power (which is a function of both distance and shadow losses) or the average carrier-to-interference ratio as the criterion for the base station assignment [11], [12]. The base station assignment strategy is likely have an impact on the estimated performance, and perhaps even more so, when considering system performance with non-stationary base stations. Here, we evaluate the coded bit error performance and the reverse link capacity based on both distance and average received power criteria for the base station assignment, and compare their relative performance. We capture the non-stationary base station scenario by allowing a cell-of-interest to move with respect to two tiers of interfering cells, and estimate the capacity at the moving cell-of-interest as a function of both fractional cell overlap and open-loop power control error. We also estimate the performance at the cell-of-interest when its base station is kept stationary while the cells surrounding it are allowed to move around. Finally, to illustrate the efficiency of the open-loop power control in terms of system capacity, we provide a comparison between the capacities achieved using open-loop power control in a LEO satellite system with those obtained with closed-loop power control in a terrestial system.

The rest of the paper is organized as follows. The open-loop power control algorithm, the system model, and the power control error statistics are presented in Section 2. The reverse link capacities (single cell as well as multi-cell) as a function of open-loop PCE for the static base station scenario are obtained in Section 3. In Section 4, system capacities with moving base stations are estimated. An open-loop *vs* closed-loop power control performance comparison is also given. Section 5 provides the conclusions.

2 – Open-Loop Power Control

In the proposed open-loop power control algorithm, the mobile estimates the state of the channel on the forward link and uses this as an estimate of the reverse link channel state. The algorithm produces an estimate of the received power at the mobile by averaging the sum of the squares of the RAKE receiver tap outputs. We consider the channel to undergo frequency selective multipath fading with log-normal shadowing. This might be the typical scenario in a land mobile satellite system when, for example, the user is under a tree or in the shadow of a tall building. The time-variant frequency-selective channel is modelled as a tapped delay line with tap spacing T_c (the chip duration), and tap coefficients $\{z_l(t)\}$ which are zero-mean, complex-valued, stationary, mutually independent, Gaussian random processes [13]. Thus, the complex lowpass equivalent channel impulse response, in the presence of shadowing, is given by

$$h(\tau;t) = S(t) \sum_{l=0}^{L_p-1} z_l(t)\delta(\tau - lT_c), \tag{1}$$

where $S(t)$ represents the amplitude of the shadowing component and is assumed to be log-normally distributed, i.e., $S(t) = e^{\zeta(t)}$, where $\zeta(t)$ is Gaussian distributed with mean $\overline{\zeta}$ (dependent on base-to-mobile distance) and standard deviation σ_ζ. This mean and standard deviation are in units of nepers (To convert to the more commonly used unit of decibels, multiply by $20/\ln 10$). The parameter L_p is the number of resolvable paths, each spaced T_c apart. If the multipath spread is T_m, then the number of resolvable paths is $L_p = \lfloor T_m/T_c \rfloor + 1$, and T_m is assumed to be less than T, where T is the bit interval. We can also write $z_l(t) = \alpha_l(t)e^{j\phi_l(t)}$, where the $\{\alpha_l(t)\}$ are Rayleigh distributed and the phases $\{\phi_l(t)\}$ are uniformly distributed in $[0, 2\pi)$. The average path strength Ω_l is the second moment of α_l (i.e., $\Omega_l = \mathrm{E}[(\alpha_l)^2]$), and is assumed to be related to the second moment of the initial path strength by

$$\Omega_l = \Omega_0 e^{-\mu l}, \qquad \mu \geq 0. \tag{2}$$

Equation (2) describes the decay of the average path strength as a function of path delay; the parameter μ reflects the rate at which this decay occurs. The shape of the decay function is referred to as the multipath intensity profile (MIP), which is assumed to be exponential. Note that the channel model described above corresponds to a flat fading channel model when $L_p = 1$.

Since we average the sum of the squared output of each RAKE receiver tap to get the received power estimate, the time-varying statistics of $\alpha(t)$ and $\zeta(t)$ are of interest. However, because such statistics are not immediately available for mobile satellite channels, those statistics that are available for terrestrial mobile radio channels are alternatively applied. In particular, for a land mobile channel, with $\alpha(t)$ Rayleigh distributed, the correlation function of $\alpha^2(t)$ is given by [14]

$$\begin{aligned} R_{\alpha^2}(\tau) &= \mathbf{E}\{\alpha^2(t)\alpha^2(t+\tau)\} \\ &= 4\sigma^4[\rho^2(\tau) + 1], \end{aligned} \tag{3}$$

where $2\sigma^2$ is the power of the Rayleigh component. The quantity $\rho(\tau)$ is the normalized autocovariance function of the complex Gaussian random process whose envelope is the Rayleigh process. If the received waves are travelling only horizontally, i.e., there is no vertical component, then from [15],

$$\rho(\tau) = J_0(2\pi f_d|\tau|), \tag{4}$$

where $f_d = v/\lambda$ is the Doppler bandwidth, v is the speed of the mobile relative to the base station, and λ is the wavelength (we assume that the system bandwidth is much smaller than the absolute value of the carrier frequency). $J_0(.)$ is the Bessel function of the first kind of zero order. In [16], the more general case of angles of arrival in the vertical plane is examined for realistic distributions. It is found that for vertical angles of arrival less than 45°, $\rho(\tau)$ is quite close to (4). Regarding the statistics of the shadowing component $\zeta(t)$, based on empirical results, the covariance function of $\zeta(t)$ on a land mobile channel is given as [17]

$$\begin{aligned} C_\zeta(\tau) &= \mathbf{E}\{\zeta(t)\zeta(t+\tau)\} - \mathbf{E}^2\{\zeta(t)\} \\ &= \sigma_\zeta^2 e^{-v|\tau|/X_c}, \end{aligned} \tag{5}$$

where X_c is the correlation distance, which has been measured as hundreds of feet for terrestial macro cells, and tens of feet for microcells. In either case, a comparison of the autocovariances of the fading and shadowing shows that the shadowing process is much more slowly varying than the fading process for velocities in the range of interest. Hence, it will be assumed that the shadowing is constant over the interval of observation. Further, the forward link is considered to be coherent. This is achieved by the transmission of a pilot tone, which consists of a pure spreading sequence (no data) at a sufficient power level. The multipath fading component on the forward link is assumed to be uncorrelated with that on the reverse link (i.e., the forward and reverse link frequency bands are considered to be separated by more than the coherence bandwidth of the channel). On the other hand, the shadowing components on the forward and reverse links (which are caused by blockage and distance) are assumed perfectly correlated. As a result, the primary purpose of the open-loop APC algorithm at the mobile is to provide an estimate of the shadowing component.

Using (1), the complex lowpass equivalent received signal at the mobile is given by

$$r(t) = S(t) \sum_{l=0}^{L_p-1} \alpha_l(t) e^{j\phi_l(t)} \sum_{k=1}^{J} c_k(t - lT_c) + n(t), \tag{6}$$

where $c_k(t)$ is the spreading sequence of the k^{th} user (a binary square waveform with chip time equal to T_c), J is the number of active users, and $n(t)$ is the complex valued low pass equivalent additive white Gaussian noise with two-sided power spectral density η_o. In (6), we have assumed that the shadowing is the same on each path. Also, it can be seen that the downlink is synchronous, since the gateway/base station has timing knowledge of all users' signals.

2.1 – Power Control Error

We estimate the received power at the mobile as shown in Figure 1. In order to estimate the received power, the outputs of the taps of the RAKE receiver are first individually correlated with the despreading sequence over one bit time, then squared and summed to yield $X(k)$ at time kT. An estimate of the received power is then formed by averaging $X(k)$ over m bits. The power estimate at time mT is given by $\widehat{S^2}(mT)$, and the mobile uses this estimate to modify its transmitted amplitude. Specifically, its transmit amplitude is inversely proportional to $(\widehat{S^2}(mT))^{1/2}$. Taking into account a round trip delay of D bits, the received signal at the base station will contain a term similar to (6), except weighted by the inverse of $(\widehat{S^2}(mT))^{1/2}$, and including the effects of the asynchronous multiple access interference (MAI), the received signal at time $m'T = (m + D)T$ is

$$r'(m'T) = \gamma \sum_{l=0}^{L_p-1} \alpha_l'(m'T) + MAI(m'T) + n'(m'T), \tag{7}$$

where the power control error γ is defined as

$$\gamma = \frac{S(m'T)}{(\widehat{S^2}(mT))^{1/2}}. \tag{8}$$

The superscript primes indicate the reverse link. Again, notice that the shadowing terms on both the links are the same, whereas the fading, noise, and multiple access interference terms are different on both links. Since the forward link is synchronous, if orthogonal codes are used for different users, the forward link MAI is mainly due to the inter-chip interference caused by the frequency selectivity of the channel; whereas, the MAI on the reverse link is introduced further by the asynchronous nature of the other users' transmissions. The distribution of the open-loop power control error, γ, is of interest; particularly, the standard deviation of the PCE can be used to quantify the performance of the open-loop APC. Analogous to the technique in [18] and [6] which showed that the distribution of the power control error on a frequency non-selective fading channel can be approximated as log-normal for a range of values of interest of X_c/λ, measurement interval and vehicle speed, we resorted to simulations to estimate the distribution and standard deviation of the open-loop PCE, σ_e, in dB on *frequency-selective* fading channels [7]. We briefly summarize those results for frequency selective fading here.

2.2 – Results

Simulation results showed that [7] the distribution of the open-loop PCE can be approximated by a log-normal distribution, even when the channel is frequency selective. It is also found that the forward link multiple access interference has very little effect on the standard deviation of the PCE, σ_e. In fact, when there is no multiple-access interference (i.e., $J = 1$), the estimated σ_e is 2.38 dB, which worsens to 2.42 dB when there are 100 users active in the system ($J = 100$) with a processing gain of 128, $L_p = L_r = 3$, $\mu = 0.2$, $m = 20$, and $f_d T = 0.05$. This corresponds to a degradation of just around 2 %, and is due to the fact that orthogonal Walsh codes were used for different users, and hence, the MAI was caused mainly by the multipath. It is further observed that σ_e decreases for increasing values of both measurement interval, m, as well as the normalized doppler bandwidth, $f_d T$ (corresponding to an increase in the vehicle speed). The reason for this is that an increase in Doppler bandwidth results in an increase in the fading rate of the Rayleigh fading process (equivalently, a decrease in the correlation of the Rayleigh process). Heuristically, this means that we are trying to average out a signal which is fluctuating more rapidly (since it is less correlated), and thus the variance of our estimate will decrease. The same explanation is valid when the measurement interval increases, i.e., over the span of the measurement interval, we observe more fluctuations, which results in a reduced variance of the estimate. Figure 2 shows the effect of increasing the number of taps in the RAKE receiver (L_r), in which we perform maximal ratio combining of all the resolvable paths (L_p). It is seen that as the number of RAKE receiver taps is increased, the power control error decreases. As can be seen from Fig. 2, the value of σ_e decreases from 3.37 dB for the flat fading case ($L_p = 1$) to 2.7 dB for the frequency selective case with a 9 tap RAKE receiver when $f_d T = 0.01$, $m = 40$, and $\mu = 0.2$. As we will see next, a reduction in PCE standard deviation of about a dB can result in significant improvement in the system capacity.

3 – Static Base Station Scenario

In this section, we estimate the reverse link capacity of both a single cell as well as a multi-cell DS-CDMA system that employs open-loop power control as described in the previous section. The results presented in this section are for a system where all the base stations are kept static. In the following, we describe the system model and the quasi-analytic approach we adopt to estimate the reverse link capacity.

3.1 – System Model

A cellular DS-CDMA system with 25 cells in a square grid layout as shown in Figure 3 is considered. We are interested in the performance at the cell-of-interest with B_{13} as its base station. The cell-of-interest is surrounded by two tiers of interfering cells. Each cell has J mobile, asynchronous users which are uniformly distributed over the cell area. Each user is power controlled based on the measurements made on the forward link from its assigned base station. For the allocation of a base station to each mobile, we consider two different models *viz.*, 1) a distance model, and 2) a power model.

Distance Model

In this model, a mobile user is assigned to a base station B_x for which the mobile-to-base distance, d_x, is minimum, i.e., x is the base station index for which

$$d_x = \min\{d_y\}, \quad y \in \{1, 2, .., 25\}. \tag{9}$$

This model is used in [10] 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

Here, a mobile is assigned to a base station from which it receives maximum average power. This power can be measured on pilot signals which are generally broadcast by the base stations at a constant power to allow the mobiles to synchronize. The variations due to fast fading are assumed to be averaged out in the measurement process such that the received power is proportional to only distance and shadow losses. Thus, a mobile is assigned to a base station B_x, where x is the base index for which

$$d_x{}^{-\nu} 10^{(\zeta_x/10)} = \min\left\{d_y{}^{-\nu} 10^{(\zeta_y/10)}\right\}, \ \ y \in \{1, 2, .., 25\}, \tag{10}$$

and where ν is the distance loss exponent (typically in the range 2 to 5.5, depending on the environment), and ζ_x corresponds to the shadow loss parameter which is assumed to be a Gaussian random variable with zero mean and standard deviation σ_ζ dB. Typically, σ_ζ varies in the range 4 - 12 dB.

Due to adaptive power control, the signals from all in-cell users arrive at the base station with nominally equal power (except for the power control error which is log-normally distrbuted, and 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 base station-of-interest B_{13}, is proportional to two factors, namely, a) attenuation caused by distance and shadowing to the base station-of-interest, B_{13}, 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,

$$I(d_{13}, d_m) \propto \left(\frac{10^{(\zeta_{13}/10)}}{d_{13}{}^{\nu}}\right) \left(\frac{d_m{}^{\nu}}{10^{(\zeta_m/10)}}\right), \tag{11}$$

where d_m and d_{13} are the distances of the out-of-cell interfering user to its own base station B_m, and to the base station-of-interest B_{13}, respectively. The variables ζ_m and ζ_{13} are shadow loss parameters which are assumed to be independent, Gaussian random variables with zero means and equal standard deviations of σ_ζ dB.

Now consider each user communicating with the base station on the reverse link using coherent BPSK modulation, rate-1/3 convolutional encoding, and direct sequence spreading. Each user is assigned a unique spreading sequence, and 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 coded symbol and chip durations, repectively, and N_c is the number of chips/coded symbol. Let $c_k(t)$ denote the code sequence waveform of the k^{th} user, and let $\{{c_i}^{(k)}\}$ be the corresponding sequence of elements of {+1, -1}. Then

$$c_k(t) = \sum_{i=-\infty}^{\infty} {c_i}^{(k)} P_c(t - iT_c), \tag{12}$$

where

$$P_c(\tau) \triangleq \begin{cases} 1 & 0 < \tau < T_c \\ 0 & \text{otherwise.} \end{cases} \tag{13}$$

Similarly, let $b_k(t)$ be the data waveform which, again, is a sequence of {+1, -1}. It follows that the transmitted signal, taking into account the open-loop power control error, for the k^{th} user is given by

$$s_k(t) = \text{Re}[A\lambda_k b_k(t) c_k(t) e^{j(\omega_o t + \theta_k)}], \tag{14}$$

where $A = \sqrt{\frac{2E_b}{T_b}}$ is common to all users, E_b is energy per coded symbol, ω_o is the common carrier frequency, θ_k is the carrier phase of the k^{th} user, and λ_k is the power control error which is a log-normally distributed random variable with standard deviation σ_e dB. Assuming asynchronous operation, the signals from all the users (other than the user-of-interest) are misaligned with respect to the signal from the user-of-interest by an amount τ_k, k = 2, 3, .., $25J$, such that τ_k is uniformly distributed in $[0, T_b)$. Consequently, the received signal at the test base station B_{13} is given by

$$r(t) = \sum_{k=1}^{25J} A\lambda_k \mu_k \sum_{l=0}^{L_p - 1} \alpha_k^{(l)} b_k(t - \tau_k) c_k(t - \tau_k) \cos(\omega_o t + \phi_k) + n_w(t), \tag{15}$$

where

$$\mu_k = \begin{cases} 1 & \text{if } k = \text{in-cell user} \\ \left(\frac{d_{m_k}}{d_{13_k}}\right)^{\nu/2} 10^{(\zeta_{13_k} - \zeta_{m_k})/20} & \text{if } k = \text{out-of-cell user,} \end{cases} \tag{16}$$

and $n_w(t)$ represents the additive white Gaussian noise component. Note that $\phi_k = \theta_k - \omega_o \tau_k$, and $\theta_1 = \tau_1 = 0$, where θ_1 and τ_1 are the carrier phase and the time delay, respectively, of the user-of-interest. Further, $\{\phi_k\}$, $k = 2, 3, .., 25J$, are independent, identically distributed random variables uniformly distributed in $[0,\ 2\pi)$, and $\{\alpha_k^{(l)}\}$ are Rayleigh random variables representing fading due to multipath. At the base station, the received signal is coherently despread and demodulated using a RAKE receiver.

3.2 – Capacity Estimation

Since practical DS-CDMA systems rely heavily on coding to improve bit error performance in the presence of fading (e.g., a rate-1/3 convolutional code is used on the reverse link in IS-95 [1]), we need to estimate the coded bit error performance in order to obtain the capacity estimates. Deriving the coded BER peformance through analytical means alone is complex, particularly when moving base stations are considered in the system. Simulation techniques using Monte Carlo or importance sampling techniques are common [19]. Monte Carlo simulation of coded systems can take prohibitively long run-times. However, from the basic properties of the code, it is possible to calculate an approximation to, or a bound on, the coded BER performance based on the BER at the decoder input[1], which is obtained through simulations. We adopt such a quasi-analytic approach to estimate the reverse link capacity.

We first estimate the channel BER of the DS-CDMA system at different system parameter settings, through large scale simulations. The occurrence of bit errors in such simulation experiments would be *bursty* due to sudden and deep fades appearing on the channel. In practice, the bursty nature of the errors due to the memory on the channel can be manipulated to appear as independent *random errors* by interleaving the coded data over sufficient depth before transmission, and deinterleaving the data before decoding at the receiver. Here, 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 coded BER performance can be upper-bounded by the well known transfer function bound [13]

$$p_o < \sum_{i=x_f}^{\infty} \beta_i P(i), \tag{17}$$

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 $N = 1$ [20]. $P(i)$ is the probabilty of selecting the incorrect path, and can be bounded by the expression

$$P(i) < [4p_c(1-p_c)]^{i/2}, \tag{18}$$

[1]We refer to the BER at the Viterbi decoder input as the *channel BER*, p_c.

where p_c is the channel 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 coded BER performance needed by the specific application (e.g., 10^{-3} for voice). A similar approach could be taken to estimate performance with soft decision decoding (which is expected to perform better than hard decision decoding), provided that the simulation is used to generate the transition probabilities of the channel transition probability matrix instead of channel BER [19]. Since our simulations primarily generate the channel BER, we restrict our results to hard decision decoding.

3.3 – Results and Discussion

The reverse link of the DS-CDMA system has been simulated, using a set of DS-CDMA simulation tools developed in C language, and the channel BER, p_c, is estimated at different system parameter settings. An information rate of 8 Kbps (which is typical of encoded voice transmission), and a rate 1/3 convolutional code of constraint length 9 are used. Random binary sequences of length 127 per coded symbol are used as the spreading sequences for different mobiles. All the mobiles transmit asynchronously with different time delays τ_k with respect to the user-of-interest, such that τ_k is chosen randomly in the set $\{0, T_s, 2T_s, ..., (N_c K - 1)T_s\}$, where T_s is the sampling interval, and K is the number of samples per chip. A sampling rate corresponding to 4 samples per chip is employed. Consistent with the previous studies [1], [10], the propagation exponent ν is taken to be 4 in all the simulations. Rayleigh fading samples are generated once every bit interval. This means that the fade is assumed to remain constant over one bit interval, which is a reasonable assumption [6]. System parameters such as the number of mobile users per cell (J), the standard deviation of the power control error (σ_e), the number of resolvable paths etc., are varied to estimate their effect on the channel BER, and hence on the system capacity. Since the system is essentially interference limited, all the simulations are carried out with no AWGN. To calculate the coded BER from the channel BER, the necessary $\{\beta_i\}$ coefficients (in Equation (17)) for the rate-1/3 code of constraint length 9 are taken from [20].

Single Cell Capacities

First we consider a single cell system with flat Rayleigh fading ($L_p = 1$). The upper bound on the coded BER performance of the system as a function of the number of interfering users (J), and σ_e, is plotted in Figure 4. It is seen that, for a target coded BER of 10^{-3}, a maximum of 33 simultaneous users can be accomodated in the system with perfect open-loop power control (i.e., $\sigma_e = 0$ dB). Note that the σ_e value of zero corresponds to the ideal power control situation where the distance and shadow losses are perfectly compensated for on the reverse link and the rapid fading due to multipath and vehicle motion remains unaffected. The same order of capacity is achieved (32 users) when $\sigma_e = 1$ dB. However, the capacity degrades by 18% (27 users) and 36% (21 users), when $\sigma_e = 2$ dB and 3 dB, respectively. Note that these capacity estimates primarily indicate the effect of power control error, without taking into account voice activity, antenna diversity at the base station, and sectorization, which are expected to improve the overall system capacity.

Next, we consider a frequency selective Rayleigh fading channel with an exponential decaying multipath intensity profile. The total received powers in both flat fading ($L_p = 1$) and frequency selective fading ($L_p > 1$) are kept the same. The number of resolvable paths, L_p, is taken to be 3. A MIP exponent value of 0.2 is taken. A RAKE receiver with maximal ratio combining of all the resolvable paths (i.e., $L_r = L_p = 3$) is used. Based on the estimated upper bound on the coded BER, the reverse link capacity at different bit error rates (10^{-3} for voice, and 10^{-6} for data) are evaluated and summarized in Table 1. It is found that with no power control error (i.e., $\sigma_e = 0$ dB), 75 and 48 simultaneous voice (10^{-3}) and data (10^{-6}) circuits, respectively, can be supported on the reverse link by the system considered. These capacity figures degrade by less than 5% when the standard deviation of PCE (σ_e) is 1 dB. When σ_e is 2 dB, the capacity degrades up to 25%. The capacity degradation becomes substantially higher when σ_e increases beyond 2 dB ($> 35\%$ for $\sigma_e = 3$ dB). Note the increased capacity achievable when the channel is frequency selective. However, also note that all these capacity estimates are optimistic, since a single cell system is devoid of any interference from adjacent cells. In the following, we study a system with multiple cells and compare its performace with the single cell performance.

Multi-cell Capacities

We estimate the bit error performance and the reverse link capacity, taking into account the effect of power-controlled interfering users from adjacent cells. For the multi-cell scenario, we use the 25 cell square grid layout shown in Figure 3, other commonly used cell layouts being hexagonal and circular [1], [10]. First, we simulate the static base stations scenario to evaluate and compare the channel bit error performance of the system under the two different base allocation models, over a flat fading channel. The simulation results with the distance model are compared with the analytical results of [10]. Figure 5 shows the channel BER performance of the reverse link as a function of number of mobile users per cell (J) when there is no AWGN, no power control error (i.e., $\sigma_e = 0$ dB), and the shadow loss parameter σ_ζ is 6 dB. The analytical performance as per [10] for the 25-cell square grid layout is also plotted. The analytical and simulation results for the distance model of base allocation are in close agreement with each other. In addition, the power model of base allocation shows better BER performance compared to distance model of base allocation. 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 [1] 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 provide 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 5. 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 6, we plot the upper bound on 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 system, over a flat fading channel. 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 coded 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 consistent with the results reported in [1]. Figure 6 also shows the BER curves for a 25-cell system when the standard deviation of the power control error, σ_e, is both 1 dB and 2 dB. It is found that the capacity reduces to 19 users (around 10 % degradation compared to no PCE case) when $\sigma_e = 1$ dB, and further degrades to 17 users (around 19 % degradation compared to no PCE case) when $\sigma_e = 2$ dB. The corresponding results for a frequency selective fading channel are shown in Figure 7 for $L_p = L_r = 3$ and $\mu = 0.2$. Here, due to the other-cell interference, the reverse link capacity degrades from 75 users in a single cell system to 42 users in a 25-cell system, corresponding to a 44 % degradation in capacity. In the presence of power control error, the 25-cell system capacity degrades to 39 users (7 % degradation compared to 42 users) when $\sigma_e = 1$ dB, and 34 users (19 % degradation) when $\sigma_e = 2$ dB. Thus, once again the capacity advantage of the frequency selective channel is seen.

4 – Moving Base Station Scenario

In the previous section, we studied the open-loop power control performance in a system with static base stations. Recently, there is growing interest and need to study cellular systems which, in addition to user mobility, support mobility of the base stations. Moving base stations can effectively be used to address the much needed system flexibility and rapid deployability concerns that are crucial in tactical and emergency communication scenarios. For example, in a tactical environment, highly integrated base stations could be mounted on jeeps, tanks, or even unmanned airborne vehicles that move along with the users as a cell. It must be noted, however, that while moving base stations do offer system flexibilty, there is the added cost of increased system complexity. Several issues can arise when moving base stations are deployed to co-exist with other static base stations in a cellular infrastructure. Primarily, base station mobility causes cells to overlap. Hence, issues like dynamic resource allocation, base station assignment, handoff, power control, etc., become critical as base stations move around. The resulting dynamic variations in multiple access interference levels under such cell overlap situations can affect the system performance in terms of capacity. The key issue we address here is how moving base stations affect the reverse link capacity at the static base stations surrounding them. In addition, the effect of base station mobility on the capacities of the moving base stations themselves are estimated. The effectiveness of the open-loop power control in a moving base station scenario is studied by estimating the capacity as a function of the degree of cell overlap and power control error.

Estimating the cellular system performance with moving base stations is a vastly, complex problem. In order to simplify the complexity involved, specific directions and distances of base stations movement are considered in the study. Regarding the direction of base station movement, both horizontal and diagonal directions are the most illustrative choices, given the symmetry involved in the square grid structure (for example, the effect of moving a base station in a horizontal direction will be identical to moving it in a vertical direction). Distances moved, on the other hand, are so chosen to allow moving base stations to get very close to the neighboring static base stations. Specifically, the performance under the following set of scenarios are estimated:

1. The cell with B_{14} as its base station moves *horizontally towards* B_{13}, and the capacity at B_{13} is estimated (Fig. 8(a)).

2. B_{14} cell moves *horizontally away from* B_{13}, i.e., towards B_{15}, and the capacity at B_{13} is estimated (Fig. 8(b)).

3. The cell with B_{19} as its base station moves *diagonally towards* B_{13}, and the capacity is estimated at B_{13} (Fig. 8(c)).

4. The B_{19} cell moves *diagonally away from* B_{13}, i.e., towards B_{25}, and the capacity at B_{13} is estimated (Fig. 8(d)).

5. Here, multiple base stations are allowed to move. All the first tier base stations, namely, B_7, B_8, B_9, B_{12}, B_{14}, B_{17}, B_{18} and B_{19}, are allowed to

move to the cell boundary of base station B_{13} as shown in Fig. 8(e). The capacity at B_{13} is then estimated.

6. The capacity at B_{13} is estimated when all the first tier base stations are allowed to move away from B_{13}, to the cell boundaries between the first tier and second tier cells (Fig. 8(f)).
7. The cell with B_{13} as its base station is moved towards B_{14} in a horizontal direction and the capacity at B_{13} is evaluated (Fig. 8(g)).
8. The B_{13} cell is moved towards B_{19} in a diagonal direction and the capacity at B_{13} is estimated (Fig. 8(h)).

While Scenarios 1 to 6 predict the effect on a static base station's performance as mobile base stations move toward and away from it, Scenarios 7 and 8 predict the effect on the performance of the moving base station itself as it moves.

4.1 – Results and Discussion

Table 2 shows the estimated reverse link capacities of the system on a frequency selective fading channel for the different moving base station scenarios described above. As before, the simulated system uses a processing gain of 127 chips per coded symbol, with 4 samples per chip sampling rate. The parameters L_p and L_r are taken to be 3, and μ is taken to be 0.2. The shadow loss parameter σ_ζ is taken as 8 dB, and the distance loss exponent as 4. In Table 2, the base station-of-interest is where the channel BER and capacity are estimated. Scenario 0 in Table 2 shows the results that correspond to the all-static base stations scenario studied in Section III. In the moving base station scenarios, let q be the distance moved by the moile base station from its static location. At each incremental distance of the cell movement, a fresh reallocation of base stations to all the mobiles in the system is carried out using the average received power criterion, i.e., using the power model in Section III. Note that $q = 0.0$ corresponds to the all-static base stations scenario. Negative values of q represent cell movement towards the base station-of-interest and positive values represent movement away from it. In Scenarios 7 and 8, where the base station-of-interest itself is moving, q is positive.

Scenario 1 gives the capacities at static base station B_{13}, when B_{14} moves horizontally towards B_{13}. The values of the distance moved (q) considered are -0.5 and -0.9. Note that $q = -0.5$ corresponds to the base station B_{14} being at the midpoint between its original static location and that of B_{13}. It is seen that when B_{14} moves very close to B_{13} (i.e., $q = -0.9$), the capacity at B_{13} degrades by around 10 % (from 42 users to 38 users) when $\sigma_e = 0$ dB. Note that this degradation is just due to the cell movement alone. On the other hand, the combined effect of both cell movement and power control error results in a capacity degradation of 16 % when $\sigma_e = 1$ dB (42 users *vs* 35 users), and 30 % when $\sigma_e = 2$ dB (42 users *vs* 29 users). Such increased degradation can be reduced by not allowing cells to move too close to other base stations. This is evident from the smaller capacity degradation for a lesser amount of cell overlap (e.g., 20 % degradation when $q = -0.5$ as against 30 % for $q = -0.9$).

Even though moving B_{14} close to B_{13} causes increased multiple access interference levels (and hence capacity degradation) at B_{13}, the base stations which B_{14} is moving away from (for example, B_{15}) can be subjected to proportionately less MAI levels, and this can end up improving capacities at those base stations. This phenomenon is illustrated in Scenario 2. The capacity at B_{13} is seen to improve by about 7 % (42 users *vs* 45 users) when B_{14} is moved horizontally away from B_{13} (i.e., towards B_{15}) at $q = 0.9$ and $\sigma_e = 0$ dB. This shows that the capacity improvement at a receding base station is less compared to the degradation suffered by an approaching base station. A similar trend in capacity variation is observed when the cell with B_{19} as its base station is moved in a diagonal direction toward (Scenario 3) and away from (Scenario 4) B_{13}. The q values considered here are $+/-$ 0.707 and $+/-1.25$. Note that $q = -0.707$ here corresponds to the base station B_{19} being moved to the intersection of the cell boundaries of B_{13}, B_{14}, and B_{18}. In Scenario 5, as multiple base stations (all the first tier cells) move toward B_{13} as shown in Fig. 8(e), the capacity degradation due to the cells' movement alone amounts to about 21 % (42 users *vs* 33 users), as against a 10 % degradation in Scenario 2 where there was only one moving base station. The degradation due to the combined effect of the cells' movement and power conrol error is around 38 % (42 users *vs* 26 users) when $\sigma_e = 2$ dB, as compared to a 30 % degradation in Scenario 2. The capacity gains achieved when all the first tier cells move away from from B_{13} are shown in Scenario 6. It is observed that a 17 % capacity improvement is achieved in Scenario 6, as compared to Scenario 0 (49 users *vs* 42 users) when $\sigma_e = 0$ dB. In the limit, when all the surrounding cells move far away, the system collapses to a single cell system, for which a capacity of 75 users is estimated in Section III.

It is further noted that the capacities are not only affected at the static base stations surrounding a moving base station, but also at the moving base station itself. This is evident from the results for Scenarios 7 and 8, where B_{13} happens to be both the moving base station as well as the base station-of-interest. For example, when B_{13} cell moves very close to B_{14} in a horizontal direction ($q = 0.9$), its capacity reduces from 42 users to 37 users, corresponding to around 12 % degradation, when $\sigma_e = 0$ dB. The capacity reduces to 30 users (28 % degradation) when $\sigma_e = 2$ dB. We note from the above result that the capacity degradation due to cell overlap alone is around 10 - 12 %, in contrast to the results reported in [10], where the capacity was shown to degrade much more drastically when the fractional cell overlap (q) increases beyond a certain point. This discrepancy is attributed to the distance model of base station allocation used (for analytical simplicity) in [10], which gave pessimistic performance estimates.

4.2 – Open-Loop vs Closed-Loop Performance

In situations where the round trip delay between the mobile and the base station is smaller than the correlation time of the channel (e.g., terrestial cellular systems), power control schemes with an open-loop strategy to compensate for the distance and shadow losses, and a closed-loop strategy to track the fast fading due to multipath and vehicle motion, are typically employed. In closed-loop power control, the mobiles periodically update their transmit powers based on the feedback (in the form of a power control command) from their respective base stations. The base stations generate these commands based on the received signal strengths from the mobiles. For closed-loop power control to be useful, these commands are to be sent to the mobiles at a rate faster than the fading rate of the channel. This would imply more complexity and increased signalling bandwidth needed on the forward link. Nevertheless, closed-loop power control offers much better performance than a open-loop strategy alone. The performance of closed-loop power control has been studied elaborately in [4]. Here, we briefly illustrate a comparison between the capacities obtained in an open-loop only strategy with those obtained using closed-loop power control. We provide the comparison for both the all-static base stations scenario as well a moving base station scenario.

Table 3 shows the capacities obtained using open-loop power control (OLPC) *vs* closed-loop power control (CLPC). The closed-loop strategy uses a fixed step size algorithm with a step size of 1 dB. The loop is updated at a rate of 800 Hz. The power control commands for different mobiles are generated by their assigned base stations based on perfect received signal power estimates. The channel is frequency selective with $L_p = L_r = 3$, and $\mu = 0.2$. It is seen that when all the base stations are static ($q = 0.0$), CLPC offers a capacity of 59 users, as against 42 users with OLPC for $\sigma_e = 0$ dB. When $\sigma_e = 1$ dB, CLPC supports 54 users, and OLPC supports 39 users. Likewise, 46 and 34 users are suppotred by CLPC and OLPC, respectively, for $\sigma_e = 2$dB. These results show that CLPC provides about 25 to 30 % increased capacity on the reverse link relative to OLPC. Table 3 also gives the capacities for a moving base station scenario (Scenario 8), where B_{13} is taken as the base station-of-interest and which is moving. Capacities are shown for $q = 0.707$ and $q = 1.25$ as B_{13} is moved in a diagonal direction towards B_{19}. Again, a capacity difference of the order of 30 % is witnessed in favor of CLPC over OLPC in the moving base station scenario.

5 – Conclusions

We have studied the performance of an open-loop power control scheme applicable to DS-CDMA networks. The scheme used the received power measurements made on the forward link at individual mobile units to control the transmit powers on their reverse links. Using a quasi-analytic approach, we estimated the reverse link capacity of the power control scheme in both a single cell as well as a 25-cell system. A rate-1/3 convolutional code of constraint length 9, a processing gain of 127 chips per coded symbol, and hard decision Viterbi decoding were considered. It was shown that, for both flat and frequency selective fading channels, the reverse link capacity of a 25-cell system reduced by about 40 % compared to that of a single cell system, mainly due to the other-cell interference. The open-loop power control error was shown to affect the system performance in such a way that the capacity degrades by 4 to 7 % when the standard deviation of the PCE (σ_e) is 1 dB, and degrades by around 20 % when σ_e is 2 dB. We also studied the performance of the multi-cell system with non-stationary base stations, which are typical in tactical environments. When a cell is moved very close to another static base station, the capacity at the static base station is shown to degrade by 10 to 15 %, due to cell overlap alone. Similar degradation is witnessed at the moving cell as well. The combined effect of both cell overlap and open-loop power control error resulted in about 30 % capacity degradation. Capacities were shown to improve at those base stations from which the mobile base stations move away. However, this improvement was seen to be less than the degradation suffered at those base stations towards which mobile base stations move. Further, a comparison between open-loop power control and closed-loop power control showed that closed-loop power control provides about a 25 to 30 % capacity improvement over open-loop power control, both under static as well as moving base station scenarios.

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Figure 1: Power estimation using RAKE.

Figure 2: Variation of σ_e (in dB) with number of RAKE receiver taps, L_r ($=L_p$). $\mu = 0.2$. $m = 40$. $J = 50$.

Figure 3: 25-cell square grid layout.

Figure 4: Upper bound on the coded BER performance of the open-loop power control scheme on a flat Rayleigh fading channel. Single cell.

Figure 5: Channel BER *vs* number of mobile users per cell (J) for different base allocation models. 25 cells square grid. Static base stations. Flat fading. $\sigma_\zeta = 6$ dB. $\sigma_e = 0$ dB.

Figure 6: Upper bound on the coded BER *vs* number of mobile users per cell (J). Static base stations. Flat fading. $\sigma_\zeta = 8$ dB. *a*) Single cell; $\sigma_e = 0$ dB. *b*) 25 cell square grid; $\sigma_e = 0$ dB, 1dB, 2 dB.

Figure 7: Upper bound on the coded BER *vs* number of mobile users per cell (J). Static base stations. Frequency selective fading. $L_p = L_r = 3$; $\mu = 0.2$. $\sigma_\zeta = 8$ dB. *a*) Single cell; $\sigma_e = 0$ dB. *b*) 25 cell square grid; $\sigma_e = 0$ dB, 1dB, 2 dB.

Figure 8: Moving Base Station Scenarios.

Coded BER	Reverse Link Capacity (% degradation)			
	Standard deviation of PCE (σ_e)			
	0 dB	1 dB	2 dB	3 dB
10^{-3} Voice	75 (0%)	72 (4%)	59 (21%)	48 (36%)
10^{-6} Data	48 (0%)	44 (5%)	36 (25%)	27 (44%)

Table 1: DS-CDMA reverse link capacity on a frequency selective fading channel with open-loop power control. Single cell. $L_p = L_r = 3$. $\mu = 0.2$.

Scenario #	Base Station of interest	Moving Base Station(s)	Direction of movement	Distance moved (q)	Reverse Link Capacity (@ 10^{-3} coded BER)		
					$\sigma_e = 0$ dB	$\sigma_e = 1$ dB	$\sigma_e = 2$dB
0	B_{13}	–	–	0.0	42	39	34
1	B_{13}	B_{14}	Horizontal	-0.5	39	37	33
				-0.9	38	35	29
2	B_{13}	B_{14}	Horizontal	0.5	43	41	35
				0.9	45	42	36
3	B_{13}	B_{19}	Diagonal	-0.707	40	38	33
				-1.25	36	34	28
4	B_{13}	B_{19}	Diagonal	0.707	43	40	34
				1.25	44	41	35
5	B_{13}	Fig. 8(e)	–	–	33	31	26
6	B_{13}	Fig. 8(f)	–	–	49	46	40
7	B_{13}	B_{13}	Horizontal	0.5	40	39	34
				0.9	37	35	30
8	B_{13}	B_{13}	Diagonal	0.707	39	37	32
				1.25	36	34	29

Table 2: Reverse link capacities for different moving base station scenarios on a frequency selective fading channel with open-loop power control error. $N_c = 127$. $L_p = L_r = 3$. $\mu = 0.2$.

Distance Moved (q, in diagonal direction)	Reverse Link Capacity @ 10^{-3} Coded BER					
	$\sigma_e = 0$ dB		$\sigma_e = 1$ dB		$\sigma_e = 2$ dB	
	OLPC	CLPC	OLPC	CLPC	OLPC	CLPC
0.0	42	59	39	54	34	46
0.707	39	57	37	52	32	44
1.25	36	55	34	50	29	42

Table 3: Open-loop *vs* closed-loop power control performance comparison on a frequency selective fading channel. Base station-of-interest = Moving base sation = B_{13}. $N_c = 127$. $L_p = L_r = 3$. $\mu = 0.2$.