Performance of DS-CDMA Networks on Rician Fading Channels with Open-Loop Power Control

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Abstract

This paper presents the performance of a direct sequence code division multiple access (DS-CDMA) network operating over Rician fading channels. The system employs an open-loop power control scheme, in which the power measurements made on the forward link are used on the reverse link to ensure equal average performance for all the users. The system capacity degradation as a function of the open-loop power control error (PCE) is estimated. The PCE is well approximated by a log-normally distributed random variable with standard deviation in the range 1 - 4 dB. The system performance for channel models with different Rice factors is presented. For applications requiring 10^{-3} *BER (e.g., voice), with a Rice factor of 6 dB, the capacity degradation compared to perfect power control is found to be less than 4% as long as the standard deviation of PCE* (σ_δ) *is less than 1 dB, and increases to 18% when* σ_δ *is 2 dB.*

1 Introduction

Recent trends in cellular mobile communications show growing importance for direct sequence code division multiple access (DS-CDMA) over conventional multiple access techniques like FDMA and TDMA, mainly due to the increased capacity that CDMA can potentially offer [1]-[3]. Among the various other issues, power control remains a crucial one in CDMA, as the capacity maximization and fair allocation of resources among different users largely depend on the effectiveness of the power control scheme employed [3]. Many results have been published on the capacity of asynchronous DS-CDMA systems over both frequency nonselective and frequency selective Rayleigh/Rician fading channels [4]-[6]. However, the above works assume *perfect power control,* i.e., all the user's transmissions arrive at the base station receiver with the same power, which is not true in mobile radio channels. An adaptive power control (APC) scheme (open-loop or closed-loop) is essential to compensate for the shadowing, distance losses, and fading effects. Such a power control scheme attempts to maintain a constant average performance among the users, and to reduce the multiple-access interference effects. Closed loop APC, though very effective at low vehicle speeds, may find it difficult to track the relatively fast variations associated with rapid channel fading, resulting from increased mobile velocity, increased carrier frequency, or a combination of both [3].

An alternate, and simpler form of power control, is an open-loop APC, in which the mobile estimates the channel state on the forward link and uses this to derive an estimate of the channel state on the reverse link [7]-[8]. The open-loop APC, in compensating for the large scale variations in the channel, which are the same on both links (such as shadowing), attempts to minimize the effect of the multipath fading component by averaging it out. This results in a randomly varying power control error (PCE). The statistics of the PCE of an open-loop APC scheme over Rician fading have been studied in [7] and [8]. It has been shown that the distribution of the PCE can be well-approximated by a *log-normal* random variable, and that the standard deviation of the PCE (σ_δ) typically varies in the range 1 - 4 dB, depending on the measurement time used in the open-loop power control algorithm, and the Doppler frequency.

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In this paper, we estimate the DS-CDMA system capacity under *imperfect power control.* Section 2 describes the system model, including the transmitter, channel, and the receiver. In Section 3, the simulation model for estimating the uncoded bit error performance of the system, the capacity estimation based on an analytical upper bound on the coded bit error performance, and the capacity degradation as a function of the standard deviation of PCE, are discussed. Section 4 highlights the conclusions.

2 System Model

We consider a DS-CDMA system consisting of $(J+1)$ simultaneously transmitting mobile users, J being the number of interfering users excluding the user of interest. Each user is assigned a unique CDMA code sequence, which modulates the data bits along with the carrier. The code 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 number of chips/bit (also the processing gain). 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

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

where

$$P_c(t) = \begin{cases} 1 & 0 < t < T_c \\ 0 & \text{otherwise.} \end{cases}$$

Similarly, the data waveform can be written as

$$b_k(t) = \sum_{i=-\infty}^{\infty} b_i{}^{(k)} P_b(t - iT_b).$$

It follows that the transmitted signal for the k^{th} user is given by,

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

where 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 random variable due to imperfect open-loop power control. We consider λ_k to be log-normally distributed with standard deviation σ_δ dB. In otherwords, $\lambda_k = 10^{(\frac{x}{20})}$, where the variable x has a normal distribution.

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, $k = 1, 2, .., J$, such that τ_k is uniformly distributed in $[0, T_b)$. Thus, the composite signal at the input to the channel is given by,

$$S(t) = \mathrm{Re}[\sum_{k=0}^{J} \lambda_k b_k(t - \tau_k) c_k(t - \tau_k) e^{j(\omega_o t + \phi_k)}], \quad (1)$$

where $\phi_k = \theta_k - \omega_o \tau_k$, and $\theta_0 = \tau_0 = 0$. Note that θ_0 and τ_0 are the carrier phase and the time delay, respectively, of the user of interest. Further, $\{\phi_k\}$, $k = 1, 2, .., J$, are independent identically distributed random variables uniformly distributed in $[0, 2\pi)$.

The channel between the mobile and the base station is modelled by Rician multipath fading, where the received signal consists of a direct specular (line-of-sight) component and several Rayleigh fading components. Assuming L_p different fading paths, the complex low pass equivalent channel response is written as

$$h(\Delta; t) = Ae^{j\varphi}\delta(\Delta - \zeta) + \sum_{i=1}^{L_p} z_i(t)\delta(\Delta - iT_c), \quad (2)$$

where $A = \sqrt{\frac{2E_b}{T_b}}$ is the amplitude of the specular path, φ and ζ are the phase and delay of the specular path, respectively, and $\{z_i(t)\}$ are zero-mean, complex-valued stationary, mutually independent Gaussian random processes corresponding to the Rayleigh fading paths. We can write $z_i(t) = \alpha_i(t)e^{j\psi_i(t)}$, where the $\{\alpha_i(t)\}$ are Rayleigh distributed, and the phases $\{\psi_i(t)\}$ are uniformly distributed in $[0, 2\pi)$.

Another important parameter to characterize the Rician channel is the *Rice factor,* ρ, which is defined as the ratio of the specular component power to the scatter components power. In otherwords, ρ can be expressed as

$$\rho = \frac{A^2}{2\sum_{i=1}^{L_p} \sigma_i{}^2},$$

where $\sigma_i{}^2$ is the average power in the i^{th} fading path. When $\rho = 0$, the specular path vanishes and the channel becomes a Rayleigh fading channel. On the other hand, when $\rho = \infty$, the resulting channel is a simple line-of-sight AWGN channel.

At the receiver, we adopt RAKE reception, where we coherently combine the signals from the specular path and L_r number of fading paths, where $L_r \leq L_p$. The tap weights and phases for the fading paths are assumed to be perfect estimates, which in practice can be estimated through dedicated circuits [9]. Due to simulation time constraints, the numerical results presented in this paper are only for the case of $L_p = L_r = 1$, at different values of Rice factor, ρ.

3 Capacity Estimation

We take a quasi-analytic approach [10] to estimate the bit error performance, and thus the capacity on the reverse link (mobile-to-base link) of the DS-CDMA system model described above. We first estimate the uncoded bit error performance of the 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. By making the *perfect interleaving* assumption, we evaluate an upper bound on the coded bit error performance of the system using convolutional codes with hard decision Viterbi decoding. 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).

Uncoded BER performance

The reverse link of the DS-CDMA system has been simulated to estimate the uncoded bit error performance of the system. A set of CDMA simulation tools developed in C language has been used to synthesize the simulation program. 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, 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 ($K = 4$) is employed. System parameters like number of simultaneous users (J), Rice factor (ρ), number of independent fading paths (L_p), multipath intensity profile (MIP), number of paths combined at the RAKE receiver (L_r), signal-to-noise ratio per bit, and standard deviation of the power control error (σ_δ), can be varied in the simulation program to study the effect of these parameters on the system performance.

Coded BER performance

For convolutional codes with hard decision Viterbi decoding, the bit error rate can be upper-bounded by the well known transfer function bound [9]

$$p_o < \sum_{x=d_f}^{\infty} \beta_x P(x), \tag{3}$$

where d_f is the free distance of the code, and $\{\beta_x\}$ are the coefficients in the expansion of the derivative of $T(D, N)$, the transfer function (or generating function) of the code evaluated at $N = 1$ [11]. $P(x)$ is the probabilty of selecting the incorrect path, and can be bounded by the expression

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

where p is the uncoded BER.

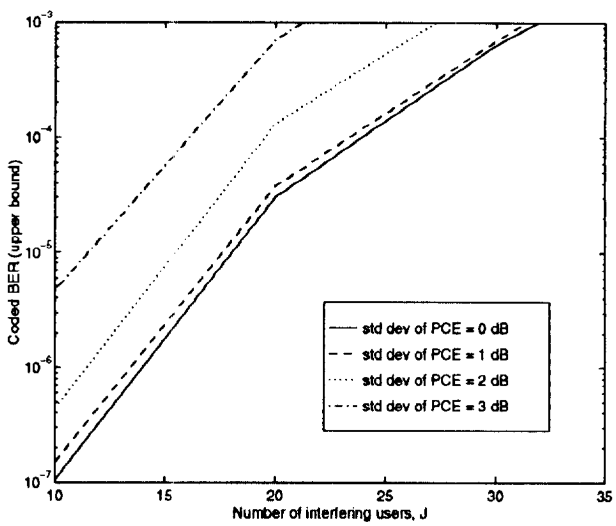

Figure 1: Flat Rayleigh fading ($\rho = 0$) - Upper bound on the coded BER *vs* number of interfering users (J) for different values of PCE standard deviation (σ_δ); No AWGN; $L_p = L_r = 1$.

Results and discussion

In this study, we consider the use of a rate-1/3 convolutional code of constraint length $K = 9$, and hard decision Viterbi decoding on the reverse link. The $\{\beta_x\}$ coefficients for the corresponding code are taken from [11]. The upper bound on the coded BER performance of the system as a function of the number of interfering users (J) is evaluated for a flat Rayleigh fading channel. Figure 1 illustrates the coded BER performance over a flat Rayleigh fading channel ($L_p = L_r = 1$ and $\rho = 0$) for different values of standard deviation of the PCE (σ_δ) in dB under no AWGN conditions. It is seen that, for a target BER of 10^{-3}, a maximum of 33 simultaneous users can be accomodated in the system with perfect power control (i.e., $\sigma_\delta = 0$ dB). The same order of capacity is achieved (32 users) when $\sigma_\delta = 1$ dB. However, the capacity degrades by 18% and 36%, when $\sigma_\delta = 2$ dB and 3 dB, respectively.

Next, the system capacity is evaluated for Rician channels with $\rho = 6$ dB and 9 dB. Because of the existence of a direct path between the transmitter and receiver, the resulting performance will be better than for the Rayleigh fading case. Figure 2 shows the performance curves for a Rician channel with $\rho = 6$ dB. The E_b/η_o on the direct path is 12 dB, and the number of scattered paths considered is 1 (i.e., $L_p = L_r = 1$). It is seen that a maximum of 83 simultaneous voice calls can be supported by the system with perfect power control ($\sigma_\delta = 0$ dB). It is interesting to note that the capacity degradation is not appreciable (< 4%), as long as σ_δ is less than 1 dB. On the other hand, substantial capacity degradation (> 18%) is observed when $\sigma_\delta \geq 2$ dB. Also, with $\sigma_\delta < 1$ dB, 50 simultaneous data circuits with 10^{-6} BER can be supported by the system.

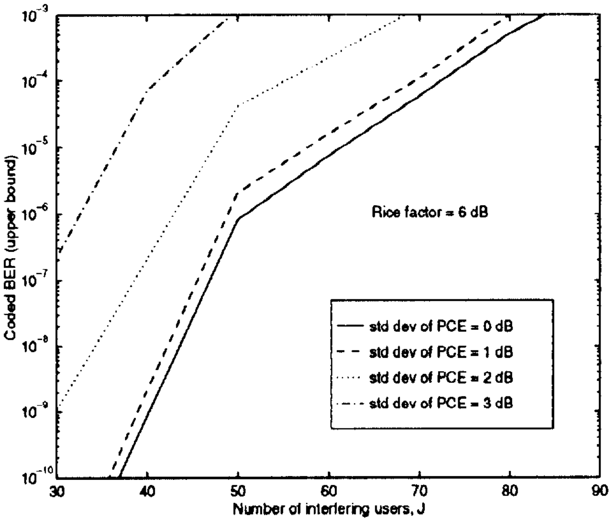

Figure 2: Rician fading ($\rho = 6$ dB) - Upper bound on the coded BER *vs* number of interfering users (J) for different vaules of σ_δ; $E_b/N_o = 12$ dB; $L_p = L_r = 1$.

Rice Factor (ρ)	$N_c = 127$; $L_p = L_r = 1$;			
	System Capacity, J (% degradation)			
	Standard deviation of PCE (σ_δ)			
	0 dB	1 dB	2 dB	3 dB
0	33 (0%)	32 (3.0%)	27 (18.2%)	21 (36.4%)
9 dB	73 (0%)	71 (2.7%)	58 (20.5%)	45 (38.3%)
6 dB	83 (0%)	80 (3.8%)	68 (18.1%)	49 (40.9%)

Table 1: DS-CDMA system capacity (number of voice circuits with 10^{-3} BER) at different Rice factors.

Table 1 summarizes the number of simultaneous voice circuits (10^{-3} BER) that can be supported for different channel conditions ($\rho = 0$, 9 dB, and 6 dB) at different values of σ_δ. In this study, we have considered just a single cell system, whereas in practical cellular systems, the effect of the dynamic adjacent cell power control variations must be considered in the system capacity estimation. Thus, our current estimates are optimistic.

4 Conclusions

We estimated the capacity of a DS-CDMA network under conditions of imperfect power control, over Rician fading channels. An adaptive open-loop power control scheme was considered. A quasi-analytical approach was adopted, wherein the uncoded bit error performance was evaluated through simulation and the coded performance was arrived through analytical bounds for a rate-1/3 convolutional code of constraint length 9, with hard decision Viterbi decoding. The system capacity degradation as a function of the standard deviation of the PCE (σ_δ) at different values of Rice factors (ρ) were presented. It was shown that a system with a processing gain of 127 and $\rho = 6$ dB can support a maximum of 80 voice circuits with 10^{-3} BER, or 50 data circuits with 10^{-6} BER, as long as the value of σ_δ is maintained within 1 dB. However, these capacities degrade by 18% and 40%, when σ_δ increases to 2 dB and 3 dB, respectively. Finally, note that these capcity estimates are optimistic, since we have not yet incorporated the effect of adjacent cell interference.

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