NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

COMBINED ADAPTIVE POWER-RATE CONTROL IN CDMA SYSTEMS

by

Dimitrios Nalmpantis

September 2001

Thesis Advisor: Tri T. Ha
Co-Advisor: Jan Tighe

Report Documentation Page

Report Date 30 Sep 2001	**Report Type** N/A	**Dates Covered (from... to)** -

Title and Subtitle Combined Adaptive Power-Rate Control in CDMA Systems	**Contract Number**
	Grant Number
	Program Element Number
Author(s) Dimitrios Nalmpantis	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Research Office Naval Postgraduate School Monterey, Ca 93943-5138	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es)	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 50	

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2001	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Combined Adaptive Power-Rate Control in CDMA Systems	**5. FUNDING NUMBERS**
6. AUTHOR(S) Dimitrios Nalmpantis	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

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14. SUBJECT TERMS CDMA cellular system, Power and rate adaptations, Imperfect power control, Co-channel interference, RAKE receiver, Nakagami fading, Lognormal shadowing.	**15. NUMBER OF PAGES** 50
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

Approved for public release; distribution is unlimited

COMBINED ADAPTIVE POWER-RATE CONTROL IN CDMA SYSTEMS

Dimitrios Nalmpantis
Captain, Hellenic Army
B.S., Hellenic Army Academy, 1989

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2001

Author: DNalmpantis
Dimitrios Nalmpantis

Approved by: Tri T. Ha
Tri T. Ha, Thesis Advisor

Jan E Tighe
Jan Tighe, Co-Advisor

Dan C Boger
Dan Boger, Chairman
Information Warfare Academic Group

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ACKNOWLEDGMENTS

This thesis is dedicated to my parents, who gave me the means to acquire my knowledge, my wife Anthoula, who supports and encourages me in every step of my life and to my son Panagiotis.

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I. INTRODUCTION

Code Division Multiple Access (CDMA) is a spread spectrum multiple access technique which is also called direct sequence multiple access and is used in cellular systems to allow many mobile users to share simultaneously a finite amount of the radio spectrum.

In a CDMA cellular system, the power levels transmitted by the mobile phone of each user are constantly controlled by the base station of the cell that serves the user. Power control is employed to ensure that each user transmits the smallest level of power necessary to maintain a grade of service quality in the reverse link [2]. By using power control, each user's transmitted signal arrives at the base station with the minimum required signal-to-interference ratio and thus, the CDMA system capacity is increased.

If the power level of every user within a cell is not controlled in such a way that the users have equal power levels at the base station receiver, then the near-far problem occurs. This is an effect that occurs when many mobile users share the same channel. Stronger received signals transmitted from users near the base station raise the noise floor at the base station receiver demodulators for the weaker signals transmitted from users far from the base station. Thus, the probability that a weaker signal will be detected decreases.

The base station in each cell implements conventional power control. It measures the received power and compensates for the channel loss by adjusting the mobile transmitted power.

Although power control is used in each cell to combat interference from other users in the cell, users from adjacent cells still cause interference, which is not controlled by the receiving base station because users from adjacent cells are power controlled by their own cell's base station.

Both large-scale fading and small-scale fading must be considered in order to have accurate power control [3]. Small-scale fading is the rapid fluctuations of the amplitude of a transmitted signal over a short period of time. Large-scale fading is due to distance path loss and a shadowing effect and it changes relatively slowly so that it can be tracked and controlled. Small-scale fading such as Nakagami fading is due to multipath propagation and it changes too fast to be controlled. A RAKE receiver is used to mitigate the effects of small scale fading.

However, the most important disadvantage of conventional power control is that it requires a large average transmit power to compensate for deep fades and to maintain a constant bit rate [6]. Another disadvantage of conventional power control is that it increases the interference caused by the mobile users located at the cell boundaries of the adjacent cells because they must transmit at a very high power level to overcome path loss and shadowing effects [5]. These problems cause a large amount of interference among other users which results in a capacity reduction of the CDMA system.

These problems of conventional power control can be solved by applying combined power and rate control that adapts to the channel fading variations. With power and rate adaptations, the transmission power can be limited when channel loss is high during deep fades. When the transmitted power goes under a threshold due to severe fading, transmission can be suspended or continued at a lower bit rate. These techniques are expected to reduce the interference caused by mobile users located at the cell boundaries and reduce the average transmit power because it does not compensate for deep fading with high transmit power. Combined power and rate control results in a capacity increase and a power gain relative to conventional power control.

II. SYSTEM MODEL

A. TRANSMITTER

The reverse channel in a DS-CDMA cellular system is the channel that carries traffic from the mobile users to the base station.

The cells in our system are modeled as hexagons, using a seven-cell per cluster architecture as depicted in Figure 1. The center cell is the cell of interest in our multi-cell analysis. It is assumed that the base station is located in the center of each cell.

Each cell is assumed to have K independent active mobile users. The kth user transmits with power P_k at a common carrier frequency $f_c = w_c / 2p$, using a data rate $R_b = 1/T_b$ and a chip rate $R_c = 1/T_c$, where T_b is the bit duration and T_c is the chip duration.

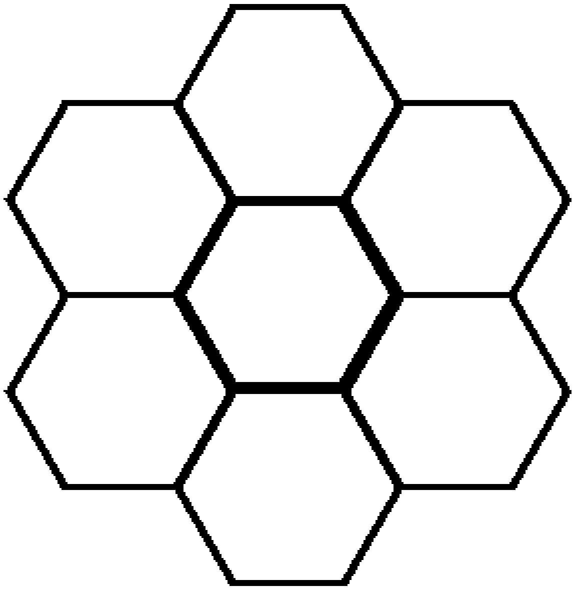

Figure 1. Seven-Cell Cluster.

From the perspective of the base station of the center cell, the composite transmitted signal $S_0(t)$ contains the traffic from the kth user of the center cell, traffic from active users of the center cell (intracell interference) and traffic from active users of the six adjacent cells (intercell interference or co-channel interference). In the following discussion, intercell interference from more than the six adjacent cells is considered to be negligible. The reverse signal $S_k(t)$ that is transmitted by the kth mobile user of the center cell to its base station will be described.

In DS-CDMA systems, the use of the bandwidth is optimized by spreading all the user traffic across the band using PN spreading signals and Walsh orthogonal covering functions for channelization [1]. The information signal of the kth mobile user in the center cell is represented as $b_k(t)$ which is a stream of binary data, where $b_k(t) = \pm 1$ for $iT_b \leq t \leq (i+1)T_b$. The data signal waveform is BPSK modulated onto the carrier at f_c and then spread by the kth user's PN spreading signal $c_k(t)$, where $c_k(t) = \pm 1$ for $jT_c \leq t \leq (j+1)T_c$. Each data bit is spread by a factor of $N = T_b / T_c$, which is also called the processing gain. In our model, a spreading factor of $N = 128$ is used.

The spread-spectrum BPSK-modulated signal that is transmitted by the kth user of the center cell is defined by

$$S_k(t) = \sqrt{2P_k}\, b_k(t) c_k(t) \cos(2\pi f_c t + \vartheta_k) \tag{2.1}$$

where P_k is the average transmit power from the kth user.

The center cell composite transmitted signal $S_1(t)$ at the input of the channel can then be expressed as

$$S_1(t) = \sum_{k=1}^{K} \sqrt{2P_k}\, b_k(t) c_k(t) \cos(2\pi f_c t + \vartheta_k) \tag{2.2}$$

The transmitted signal corresponding to K users in each of the 6 adjacent cells, for the reverse link to the base station of the cell of interest, is given by

$$S_2(t) = \sum_{i=1}^{6K} \sqrt{2P_i}\, b_i(t) c_i(t) \cos(2\pi f_c t + \vartheta_i) \tag{2.3}$$

The overall transmitted signal at the input of the channel including intracell and intercell interference is given by

$$S_0(t) = S_1(t) + S_2(t) \tag{2.4}$$

B. CHANNEL MODEL

The signal transmitted from the mobile user to the base station loses a part of its power along the way. This happens because of the distance it travels and the terrain across which it travels. The signal suffers from large-scale path loss and small-scale multipath fading [2].

Large-scale fading is due to the distance loss and shadowing effects and changes relatively slowly. Power control compensates for large-scale fading in the center cell and therefore, each active user arrives with the same power at the base station of the center cell. It is assumed that our multicell CDMA system operates with imperfect power control and thus, the effect of power control error (PCE) occurs. The PCE in the center cell is modeled as a lognormal random variable, i.e. $l = 10^{x/10}$, where $x \sim \mathrm{N}(0, s_e)$ is a Gaussian random variable of zero mean and standard deviation s_e, and s_e is the PCE in dB [3]. Power control from the base station of the center cell cannot be applied to the users from the six adjacent cells because their powers are controlled by their own base stations. In these instances, a distance path loss with an nth-order power law is assumed in order to cover a large number of propagation environments and lognormal shadowing. As seen from Figure 2, the received power at the base station of the center cell due to a user in another cell that is located at a distance r_2 from the center of the cell of interest is given by

$$P_k\left(\frac{r_1}{r_2}\right)^n 10^{\frac{(z_2 - z_1)}{10}} \tag{2.5}$$

where

r_1 = the distance of the user from the base station of his own cell

$r_1^n / 10^{(z_1/10)}$ is the power control to compensate for the attenuation from the user to the base station of his own cell

$10^{(z_2/10)} / r_2^n$ is the path loss and shadowing from the user to the base station of the center cell

$z_1 \sim \mathrm{N}(0, s_{z_1})$ and $z_2 \sim \mathrm{N}(0, s_{z_2})$ are independent Gaussian random variables of zero mean and standard deviation s_{z_1} and s_{z_2} respectively in dB , to account for a typical shadowing propagation environment.

It is assumed that the mobile users in each cell are uniformly distributed.

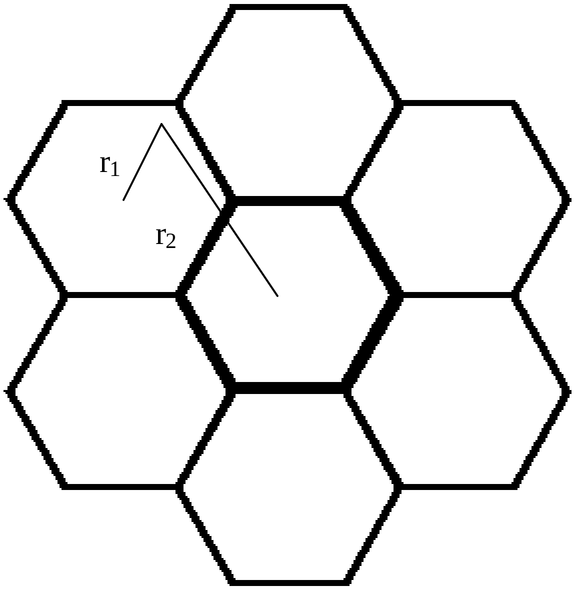

Figure 2. Power Control of Out-of-Cell Users.

Small-scale fading is due to the multipath propagation and changes a lot faster than the power control rate but much slower than the chip rate. The frequency-selective Nakagami slow fading channel is used to represent the small-scale fading effects in our channel model. It can be modeled as a linear filter with the following low-pass equivalent impulse response for the kth user [4]

$$h_k(t) = \sum_{l=1}^{L} a_{k,l} d(t - t_{k,l}) e^{-jq_{k,l}} \qquad (2.6)$$

where

d = the Dirac Delta function

$a_{k,l}$ = the set of path amplitudes

$\tau_{k,l}$ = the set of path delays

$\theta_{k,l}$ = the set of path phase shifts

k = $1,2,\ldots,K$ the number of users

l = $1,2,\ldots,L$ the number of paths due to multipath propagation

It is assumed that L is the same for all users and constant, α_l are mutually independent and identically Nakagami distributed and constant during the bit duration, θ_l are mutually independent uniformly distributed over $[0,2\pi]$ and constant during the chip duration and τ_l are mutually independent uniformly distributed over $[0,T_c]$ and constant during the chip duration.

It is assumed that the small-scale fading is characterized by the Nakagami-m distribution that has the probability density function (pdf)

$$p_R(r) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{\frac{-mr^2}{\Omega}} \tag{2.7}$$

where Ω is defined as

$$\Omega = \mathrm{E}\left[R^2\right] \tag{2.8}$$

and the parameter $m \geq 1/2$ called the fading figure is defined as the ratio of moments

$$m = \frac{\Omega^2}{\mathrm{E}\left[\left(R^2 - \Omega^2\right)\right]} \tag{2.9}$$

The Nakagami-m is a two-parameter distribution with the parameters m and the second moment Ω. As a consequence, this distribution is better in matching the signal statistics than the Rayleigh distribution because it can be used to model fading channel conditions that are either more or less severe. It has been shown that the Nakagami-m distribution is the best fit for data signals in urban radio multipath channels [7].

For $m = 1/2$, the one-sided Gaussian fading distribution results. This is the worst case fading. For $m = 1$, it is reduced to the Rayleigh distribution, and as m approaches infinity, the channel becomes non-fading.

Thus, for a channel input given by (2.4), the received signal $r(t)$ at the output of the channel is

$$r(t) = \sum_{k=1}^{7K}\sum_{l=1}^{L} a_{k,l}\sqrt{2P_k}\,b_k(t - t_{k,l})c_k(t - t_{k,l})\,l_k y(k)\cos\left[2p\, f_c\left(t - t_{k,l}\right) + q_{k,l}\right] + n(t) \quad (2.10)$$

where

$a_{k,l}$ = Nakagami random variable

l_k = lognormal random variable that represents the PCE

$n(t)$ = AWGN with single sided power spectral density N_o

$y(k)$ = 1, when $k \le K$

$y(k) = \left(\frac{r_1}{r_2}\right)^n 10^{(z_2 - z_1)/10}$, when $k > K$

The $y(k)'s$ are considered as independent random variables that represent the power control for the user belonging to one of the six adjacent cells from his own base station, and path loss with lognormal shadowing between that user and the base station of the cell of interest.

C. RECEIVER

In order to compensate for small-scale fading, the technique of diversity combining is employed at the receiver. This technique combines multiple replicas of the received signal to combat multipath impairments. In a DS-CDMA system transmitting over a frequency selective channel, diversity combining is implemented with a RAKE receiver. The basic RAKE receiver structure is a tapped delay line shown in Figure 3, which attempts to collect the signal energy from all the signal paths that fall within the span of the delay line and to combine them optimally. The RAKE receiver requires that the transmitted signal must have a bandwidth that is greater than the coherence bandwidth B_c of the channel, which is exactly the case of the DS-CDMA cellular systems that are implemented in practice [2].

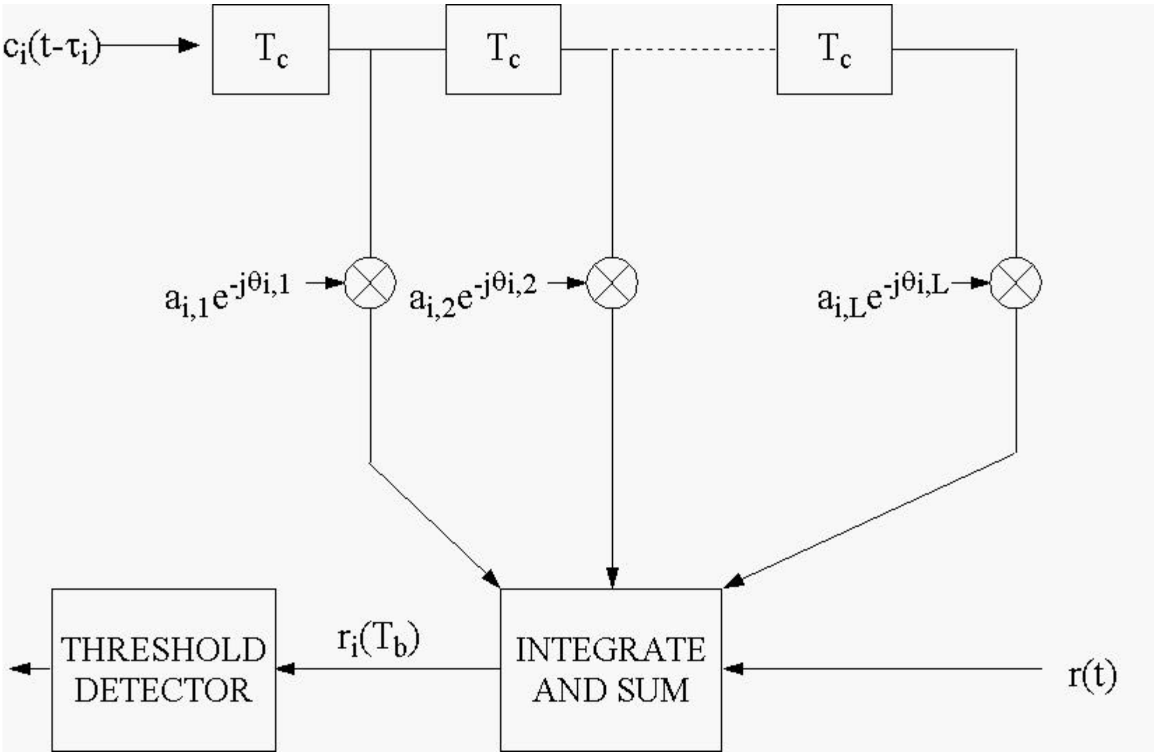

Figure 3. L-branch Optimum RAKE Receiver.

For our model, the L branch RAKE receiver with maximal ratio combining (MRC) is considered. MRC is the optimum combining technique because it provides the maximum output SNR [4]. In such a receiver, each of the L received signals is first correlated with the ith user's code waveform $c_i(t)$, and then coherently demodulated. These operations assume perfect carrier recovery and perfect knowledge of the $t_{i,l}$'s and $J_{i,l}$'s, the set of path delays and the set of path phase shifts of the ith user respectively. The L correlator outputs $r_{i,l}$ are weighted and then combined by a linear combiner to form the ith user decision statistic $r_i = \sum_{l=1}^{L} w_l r_{i,l}$, where w_l is the weight of the lth branch (finger) of the RAKE receiver. With MRC, the diversity branches are weighted by their respective fading amplitudes $a_{i,l}$ and thus we have $w_l = a_{i,l}$. Therefore MRC assumes perfect knowledge of the branches' strengths [4].

Following the analysis in [3] we know that $r_i(T_b)$, the decision statistic for the ith user, is asymptotically Gaussian distributed, conditioned on the tap weights and the PCE of the user of interest, i.e.,

$$r_i(T_b) \sim \mathrm{N}(m, s^2) \tag{2.11}$$

with mean $m = l_i A T_b \sum_{l=1}^{L} a_{i,l}^2$ and variance

$$s^2 = A^2 T_b^2 \frac{1}{3N} \sum_{\substack{k=1 \\ k \neq i}}^{K} \sum_{l=1}^{L} E[a_{k,l}^2] E[l_k^2] \sum_{l=1}^{L} a_{i,l}^2 + A^2 T_b^2 \frac{1}{3N} \sum_{k=K+1}^{7K} \sum_{l=1}^{L} E[a_{k,l}^2] E[y(k)^2] \sum_{l=1}^{L} a_{i,l}^2 + N_0 T_b \sum_{l=1}^{L} a_{i,l}^2$$

where $a_{i,l}$ are the tap weights for the ith user , $l \in \{1,2,...,L\}$ and A is the received signal amplitude without fading. In (2.11), the mean m represents the message component of the signal and the variance s^2 represents the sum of the variances of the interference terms and the noise term.

In the preceding analysis it was assumed that each user has an identically distributed PCE, which means that $E[l_k^2] = E[l^2]$, and that each user has an identical multipath intensity profile (MIP), which means that $E[a_{k,l}^2] = E[a_l^2]$. It was also assumed a rectangular pulse shape.

The signal to noise plus interference ratio is defined at the output of the receiver as a ratio of the average power in the message component of the signal, to the average power of the noise and interference components [1]. The signal to noise plus interference ratio conditioned on the tap weights and the PCE of the user of interest, is given by

$$SNIR = \frac{m^2}{s^2} =$$

$$\frac{\left(l_i A T_b \sum_{l=1}^{L} a_{i,l}^2 \right)^2}{\frac{A^2 T_b^2}{3N} \sum_{\substack{k=1 \\ k \neq 1}}^{K} \sum_{l=1}^{L} E[a_{k,l}^2] E[l_k^2] \sum_{l=1}^{L} a_{i,l}^2 + \frac{A^2 T_b^2}{3N} \sum_{k=K+1}^{7K} \sum_{l=1}^{L} E[a_{k,l}^2] E[y(k)^2] \sum_{l=1}^{L} a_{i,l}^2 + N_0 T_b \sum_{l=1}^{L} a_{i,l}^2} =$$

$$\frac{l_i^2 A^2 T_b^2 \sum_{l=1}^{L} a_{i,l}^2}{\frac{A^2 T_b^2}{3N}\sum_{\substack{k=1\\k\neq i}}^{K}\sum_{l=1}^{L} E[a_{k,l}^2]E[l_k^2] + \frac{A^2 T_b^2}{3N}\sum_{k=K+1}^{7K}\sum_{l=1}^{L} E[a_{k,l}^2]E[y(k)^2] + N_0 T_b} =$$

$$\frac{l_i^2 \sum_{l=1}^{L} a_{i,l}^2}{\frac{1}{3N}\sum_{\substack{k=1\\k\neq i}}^{K}\sum_{l=1}^{L} E[a_{k,l}^2]E[l_k^2] + \frac{1}{3N}\sum_{k=K+1}^{7K}\sum_{l=1}^{L} E[a_{k,l}^2]E[y(k)^2] + \frac{N_0}{A^2 T_b}} =$$

$$\frac{l_i^2 \sum_{l=1}^{L} a_{i,l}^2}{\frac{2}{3N}\sum_{\substack{k=1\\k\neq i}}^{K}\sum_{l=1}^{L} E[a_{k,l}^2]E[l_k^2] + \frac{2}{3N}\sum_{k=K+1}^{7K}\sum_{l=1}^{L} E[a_{k,l}^2]E[y(k)^2] + \left(\frac{E_b}{N_0}\right)^{-1}} \tag{2.12}$$

where E_b is the received bit energy without the effects of fading and power control error, and for BPSK modulation it is $E_b = A^2 T_b / 2$.

D. USER DISTRIBUTION

For each cell in our multicell CDMA cellular system we assume that the users are uniformly distributed in the entire area of the hexagonal cell. But due to power control, user distribution in the center cell has no effect to our system model. This happens because the signal of every user in the same cell arrives to its base station receiver with the same power level.

But in order to model the path loss and shadowing effect of the interfering signal from adjacent cells relative to the base station of the center cell, we have to consider another user distribution scheme. To simplify the analysis we replace the seven hexagonal cell cluster with a circular center cell and a circular disc representing the six adjacent cells, as in Figure 4. We take the center cell base station to be the origin of our system. Thus every user in the center cell has a distance r_1 to the base station of the center cell. For convenience, r_1 is normalized to the cell radius such that $0 < r_1 \leq 1$. Each user in the circular disc of the six adjacent cells has a normalized distance r_2. Note that

$1 < r_2 \le 3$. These distances are used to calculate the path loss and shadowing that result in the intercell interference.

We assume a uniform user distribution in the circular disc representing the six adjacent cells. Accordingly, the position of every mobile user belonging in one of the six adjacent cells depends only on his distance to the base station of the center cell.

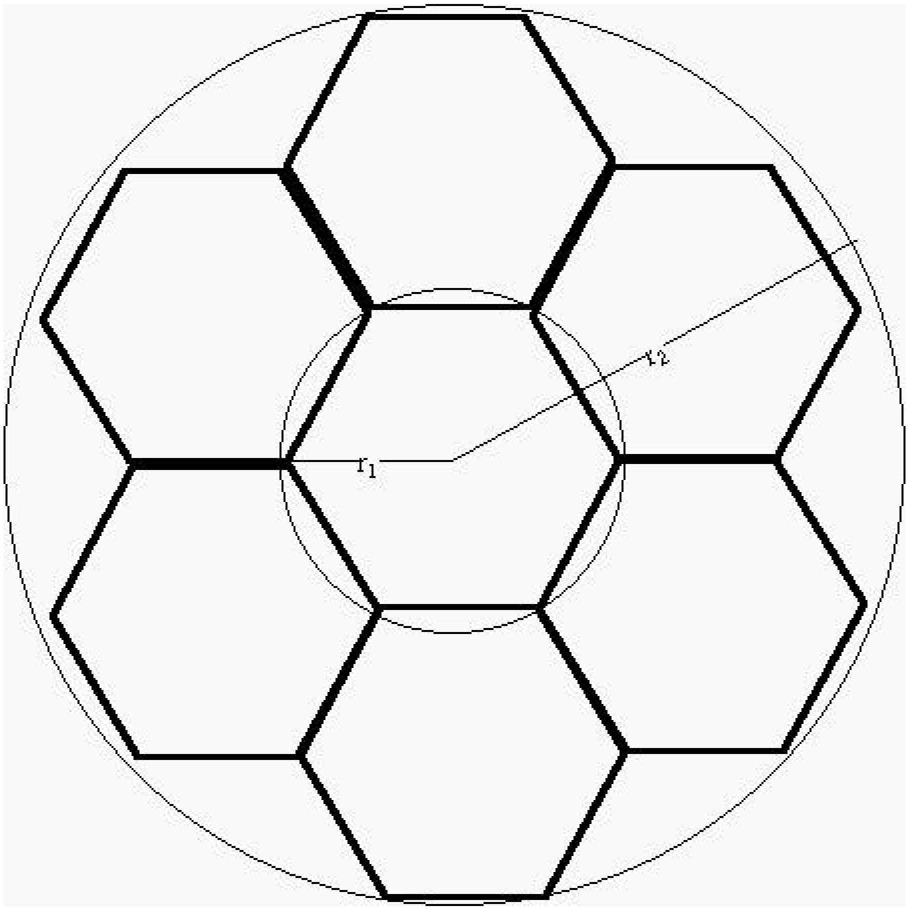

Figure 4. User Distribution in a Multicell CDMA System.

III. POWER-RATE ADAPTATIONS

In order to analyze power and rate adaptations, we consider that the channel power gain $g(t)$ consists of two components and it is given by $g(t) = G(t)L(t)$, where $G(t)$ is the gain associated with the Nakagami fading and $L(t)$ is the gain associated with path loss and shadowing. It is assumed that $L(t)$ is perfectly known to the base station receiver through measurement in real time, and that the transmit power of the mobile is adjusted accordingly to compensate for $L(t)$ since power control is used. $G(t)$ and $L(t)$ can be replaced with the random variables G and L assuming that they are constant over the chip period [5].

A. TRUNCATED POWER CONTROL

The transmit power of the kth user is $P_T(L_k)$ when the channel gain associated with path loss and shadowing is L_k. Since conventional power control is used in each cell, it is seen that $P_T(L_k) = P_O / L_k$, where P_O is the target received power, and is assumed to be the same in each cell of the CDMA system.

Truncated power control compensates for fading above a threshold g in the following way

$$P_T(L_k) = \frac{P_O}{L_k} \qquad \text{when} \quad L_k \geq g \tag{3.1}$$

$$P_T(L_k) = 0 \qquad \text{when} \quad L_k < g \tag{3.2}$$

When the channel gain L_k is higher than the threshold g, the mobile transmits. When the channel gain L_k is less than the threshold g, there is no transmission. Since the mobile transmits only when $L_k \geq g$, the activity factor $p(g)$ can be expressed as $p(g) = \Pr[L_k \geq g]$, and it is assumed to be the same in every cell of our CDMA system. The truncation probability, the probability that the mobile is not transmitting due to severe fading, is given by $1 - p(g)$. For the threshold value of $g = 0$, the truncated power control is reduced to the conventional power control, which fully compensates for deep fading by increasing the transmitted power $P_T(L_k)$ to very high levels. In that case $P_T(L_k) = P_O / L_k$ when $L_k > 0$ and the transmitted power $P_T(L_k)$ is never equal to zero because the channel gain associated with path loss and shadowing L_k can never be negative.

The potential effects of applying truncated power control in a CDMA cellular system are as follows [5]. Mobiles on the cell boundaries are more likely to have their line-of-sight to the base station blocked and therefore experience deep shadowing effect. So we expect that truncated power control will reduce interference caused by mobiles on the cell boundaries, since these mobiles will often not transmit and therefore will not contribute to intracell and intercell interference. Additionally, truncated power control reduces the average transmit power of the mobile relative to the conventional power control because it does not compensate for deep fading and as a result it prolongs the mobile phone's battery life. These two effects result in a capacity increase and a power gain over the conventional power control for the CDMA cellular system.

1. Signal to Noise Plus Interference Ratio (SNIR)

Taking into account (2.10) and (2.11) we can express the average received power in the center cell's base station receiver as

$$I = I_0 + I_1 + I_2 + N_0 T_b \sum_{l=1}^{L} a_{i,l}^2 \tag{3.3}$$

The first component I_0 of (3.3) is the average received power in the base station of the center cell due to the desired ith user

$$I_0 = \sum_{l=1}^{L} a_{i,l}^2 P_i \, p(g) \, l_i^2 \tag{3.4}$$

where $a_{i,l}$ is the Nakagami distributed fading amplitude for the desired ith user in the lth path, P_i is the average transmitted power from the ith user in the center cell, $p(g)$ is the activity factor , and l_i is a lognormal random variable representing the PCE for the ith user in the center cell.

The second component I_1 of (3.3) is the average received power in the base station of the center cell due to the users of the center cell (intracell interference)

$$I_1 = \sum_{\substack{k=1 \\ k \neq i}}^{K} \sum_{l=1}^{L} a_{k,l}^2 P_k \, p(g) \, l_k^2 \tag{3.5}$$

where $a_{k,l}$ is the Nakagami distributed fading amplitude at the lth path for the kth user of the center cell, P_k is the average transmitted power from the kth user in the center cell, and l_k is lognormal random variable representing the PCE for the kth user in the center cell.

The third component I_2 of (3.3) is the average received power in the base station of the center cell due to the users of the six adjacent cells (intercell interference)

$$I_2 = \sum_{j=K+1}^{7K} \sum_{l=1}^{L} a_{j,l}^2 P_j \, p(g) \, y_1(j) \tag{3.6}$$

where $a_{k,l}$ is the Nakagami distributed fading amplitude at the lth path for the jth user in one of the six adjacent cells, P_j is the average transmitted power from the jth user in one of the six adjacent cells, and for the case of truncated power control the term $y(j)$ in (2.10) has become

$$y_1(j) = \left(\frac{r_1}{r_2} \right)^n 10^{(z_2 - z_1)/10} \, p(g) \quad \text{when } j \geq K \, .$$

The fourth component $N_0 T_b \sum_{l=1}^{L} a_{i,l}^2$ of (3.3) is the noise variance conditioned on the tap weights and the PCE of the user of interest, which represents the total noise power.

Since the received power at the base station is the same target power P_O for every user, $P_i = P_k = P_j = P_O$ for all i, j, k .

The received bit energy E_b without the effects of fading, power control error and truncation probability is represented as $E_b = P_i T_b$ for the ith user. According to (2.12) the average bit energy-to-equivalent noise plus interference density ratio or the signal-to-noise plus interference ratio per bit for the desired ith user, conditioned on the tap weights of the RAKE receiver and the PCE of the user of interest, for the case of truncated power control, is given by

$$SNIR = \frac{E_b}{N_e} = \frac{\sum_{l=1}^{L} a_{i,l}^2 l_i^2 p(g)}{\frac{2}{3N}\sum_{\substack{k=1\\k\neq i}}^{K}\sum_{l=1}^{L} E[a_{k,l}^2]E[l_k^2]p(g) + \frac{2}{3N}\sum_{k=K+1}^{7K}\sum_{l=1}^{L} E[a_{k,l}^2]E[y_1(k)^2] + \left(\frac{E_b}{N_0}\right)^{-1}} \quad (3.7)$$

where $N = R_c T_b$ is the CDMA processing gain with the conventional power control scheme.

B. POWER AND RATE ADAPTATION

For this case, every mobile transmitter in every cell of the CDMA system is assumed to be limited to a maximum transmission power $P_{\max}$ and that with conventional power control, a full compensation of fading can be achieved if [6]

$$P_T(L_k) = \frac{P_O}{L_k} \le P_{\max} \Rightarrow L_k \ge \frac{P_O}{P_{\max}} = x \quad (3.8)$$

In this scheme

- When $L_k \ge x$, the data rate is fixed and the transmission power $P_T(L_k)$ is adjusted such that $L_k P_T(L_k) = P_O$
- When $L_k < x$, the transmission power $P_T(L_k)$ is fixed at a value P_S such that $P_S \le P_{\max}$, and the data rate is adapted such that the requirements of the quality of service can be attained

Power and rate adaptation performs the rate adaptation when the transmission power required to meet a target Quality of Service exceeds the maximum transmission limit of $P_{\max}$, and otherwise adapts the transmission power to ensure a fixed rate transmission.

Power and rate adaptation provides a power gain over the conventional power control because the conventional power control uses large transmission power in compensating for deep fading in order to maintain a constant bit rate. The power gain translates to a reduction in interference to other users, both intracell and intercell, thus leading to capacity increase because CDMA cellular systems are interference limited systems.

Special cases of the power and rate adaptation are the truncated power adaptation ($P_S = 0$) which suspends transmission when $L_k < x$, and the power adaptation or conventional power control ($x = 0$ or $P_{\max} = \infty$) which its transmit power is not limited. Power and rate adaptation saves power by limiting the transmission power $P_T(L_k)$ when $L_k < x$.

C. TRUNCATED RATE ADAPTATION

In this scheme [6] we have

- When $L_k \geq x$, the data rate is adapted with a fixed transmission power $P_{S'}$ such that $P_{S'} \leq P_{\max}$
- When $L_k < x$, the data transmission is suspended

Truncated rate adaptation suspends the transmission of data when the channel gain is below a threshold and otherwise adapts the transmission rate with a constant power.

Truncated rate adaptation provides a power gain over the conventional power control because it either suspends transmission $P_T(L_k) = 0$, or fixes the transmit power to a value less than $P_{\max}$ which is possible to reach with the conventional power control.

Truncated rate adaptation also saves power by limiting the transmission power $P_T(L_k)$ when $L_k < x$ or when the fading is severe.

A special case of truncated rate adaptation is the rate adaptation ($x = 0$ or $P_{\max} = \infty$). The rate adaptation uses a constant transmit power and compensates for severe fading by reducing the bit rate rather than using a large power. As a consequence, rate adaptation saves power during deep fades. Although the rate adaptation experiences a time delay when the channel gain is low, it can be used in data communications, where users can tolerate some delay.

IV. NUMERICAL RESULTS

In Chapter III we obtained the expression of the signal-to-noise plus interference ratio per bit for the case of truncated power control of a multicell CDMA cellular system over a frequency selective Nakagami-Lognormal channel with power control error (PCE). In order to illustrate the performance and investigate the effects of intracell interference, intercell interference, Nakagami fading, lognormal shadowing, path loss, power control error, truncation probability and sectoring we conducted Monte Carlo simulation with 100000 trials using Matlab 5.3 [8]. The numerical results are shown in Figures 5-13.

The received bit energy-to-noise density ratio E_b / N_0 without the effects of fading, power control error and truncation probability is selected at the value of 15dB. A distance path loss with a 4th-order power law is preferred in order to cover a large number of propagation environments. The processing gain $N = R_c / R_b$ of the spread spectrum CDMA system with the conventional power control scheme is selected to have the value of 128. The RAKE receiver is chosen to combine $L = 3$ paths of the received signal. Values of the parameters $m = 0.8, 1, 2$ and $\Omega = 1$ of the Nakagami fading channel are selected to provide sufficient detail in the effect of small-scale fading. For $m = 0.8$ we have the case of severe fading. For $m = 1$, the channel becomes a Rayleigh fading channel, and as m approaches infinity the channel becomes non-fading. Thus for $m = 2$ we have less fading effect. Values of the activity factor $p(g) = 1, 0.99, 0.9$ are selected to account for different cases of truncated power control. PCE values of $s_e = 0, 2, 3, 4$ dB are preferred to compensate for imperfect power control, with the value $s_e = 0$ accounting for perfect power control. Lognormal shadowing effect values of $s_{z_1} = 7, 10$ dB and $s_{z_2} = 7, 10$ dB are selected to account for a typical shadowing propagation environment, and a more severe shadowing propagation environment, respectively. Single user, single cell and multicell evaluations are considered in order to show the signal-to-noise plus interference ratio degradation due to the effect of intracell and intercell (co-channel) interference. 60^0 sectoring is employed to show the capacity increase due to the interference reduction.

In Figure 5, the $SNIR$ of the CDMA system is demonstrated as a function of the number of users per cell, with $m = 0.8$, $\Omega = 1$, $p(g) = 0.99$, $s_e = 2dB$, $E_b / N_0 = 15dB$ and $N = 128$, for the single-cell and the multicell case. We calculated the $SNIR$ for the single user case to be $20.2dB$, a value that is far better than the single cell case because of the total absence of interference caused by other users in the system. We can see that $SNIR$ in the single-cell case is superior to $SNIR$ in the multicell case. This is expected because in the single-cell case there is only intracell interference due to K users while in the multicell case there is intracell plus intercell interference due to $6K$ users of the adjacent cells. In addition, in the single cell case the effects of lognormal shadowing and path loss do not occur due to power control. We can also see that $SNIR$ in the multicell case with $s_{z_2} = 7dB$ is superior to $SNIR$ in the multicell case with $s_{z_2} = 10dB$. That is because the latter accounts for more severe lognormal shadowing which degrades more the performance of the system.

As the number of users per cell increases, intracell and intercell interference increase and thus the $SNIR$ of the system decreases.

In Figure 6, we can see the $SNIR$ of the multicell CDMA system versus the number of users per cell, with $m = 1$, $\Omega = 1$, $p(g) = 1$ meaning that truncated power control is not employed, $E_b / N_0 = 15dB$, $N = 128$ and $s_{z_2} = 10dB$. $PCE = 0dB$ accounts for perfect power control and $PCE = 2dB$ accounts for imperfect power control with standard deviation of the power control error equal to $2dB$. It can be seen that $SNIR$ in the imperfect power control case is larger than $SNIR$ in perfect power control case. That is because for the same number of users per cell our multicell CDMA system needs less $SNIR$ for the perfect power control case than the $SNIR$ for the imperfect power control case. According to [3], the bit error probability increases with the standard deviation of PCE and therefore for larger standard deviation of PCE values the system needs more $SNIR$ to compensate for the effect of imperfect power control.

Again, as the number of users per cell increases, interference increases, resulting in a decrease in $SNIR$ of the system.

In Figure 7, we can see how the effect of imperfect power control results in the multicell system performance for different values of the standard deviation of the PCE, with $m = 1$, $\Omega = 1$, $p(g) = 0.99$, $E_b / N_0 = 15dB$, $N = 128$ and $s_{z_2} = 10dB$. As we saw in the previous figure, for the same number of users per cell, the multicell system needs more $SNIR$ for imperfect power control with larger standard deviation of the power control error. As the system tries to compensate for imperfect power control with larger values of PCE, it needs more $SNIR$ to reach the same performance for the same number of users per cell.

In Figure 8, we have the same case as in the previous figure with $m = 1$, $\Omega = 1$, $E_b / N_0 = 15dB$, $N = 128$ and $s_{z_2} = 10dB$, but for an activity factor $p(g)$ value of 0.9 or truncation probability $1 - p(g)$ value of 0.1. In our multicell system for a smaller value of the activity factor we have a larger value of truncation probability, which leads to less interference because less active users are transmitting due to severe fading effect. Thus the performance of the system improves as the truncation probability increases. Accordingly, for the same number of users per cell and for a larger value of truncation probability (smaller value of activity factor), the system needs less $SNIR$ to achieve the same performance. This can be seen by comparing the two plots in figures 7 and 8. It can also be translated as a capacity gain i.e. more active users in the system for the same amount of $SNIR$ when we have a larger value of truncation probability, as it is considered and demonstrated in [5].

In Figure 9, the $SNIR$ of the multicell CDMA cellular system is depicted as a function of E_b / N_0, where E_b is the received bit energy of the signal without the effects of fading, power control error and truncation probability, with $m = 1$, $\Omega = 1$, $s_e = s_{z_1} = 2dB$, $s_{z_2} = 7dB$, $p(g) = 0.99$ and $N = 128$. We present three cases of $K = 30,40$ and 50 number of users per cell. We clearly see that for a larger number of users, the $SNIR$ of the system decreases, mainly due to the larger amount of interference that more users cause. The system performance degrades for all users as the number of users is increased, and improves as the number of users is decreased. We can also see that as E_b / N_0 increases, $SNIR$ also increases for all three cases. But after reaching a value of $14-15dB$, $SNIR$ remains practically the same for further increase of E_b / N_0, and thus the performance of the multicell CDMA system enters the interference floor region. That is because CDMA cellular systems are interference limited systems.

In Figures 10-13, results are shown for the same cases as in Figures 5-8 considering 60^0 sectoring in every cell of the CDMA system. 60^0 sectoring is employed in a cellular system by replacing a single omni-directional antenna at the base station of each cell by six directional antennas, each radiating within a specified sector [2]. Hence there are six 60^0 sectors in every cell. By using sectoring, a given sector will receive interference and transmit with only a fraction of the adjacent cells, resulting in a capacity increase of the system. The interference is reduced by a factor of 6, and thus system capacity is increased by the same factor. That is clearly shown in the plots, as the system with 60^0 sectoring and $6K$ number of users per cell or K number of users per sector, has similar performance to the unsectored system with K number of users per cell.

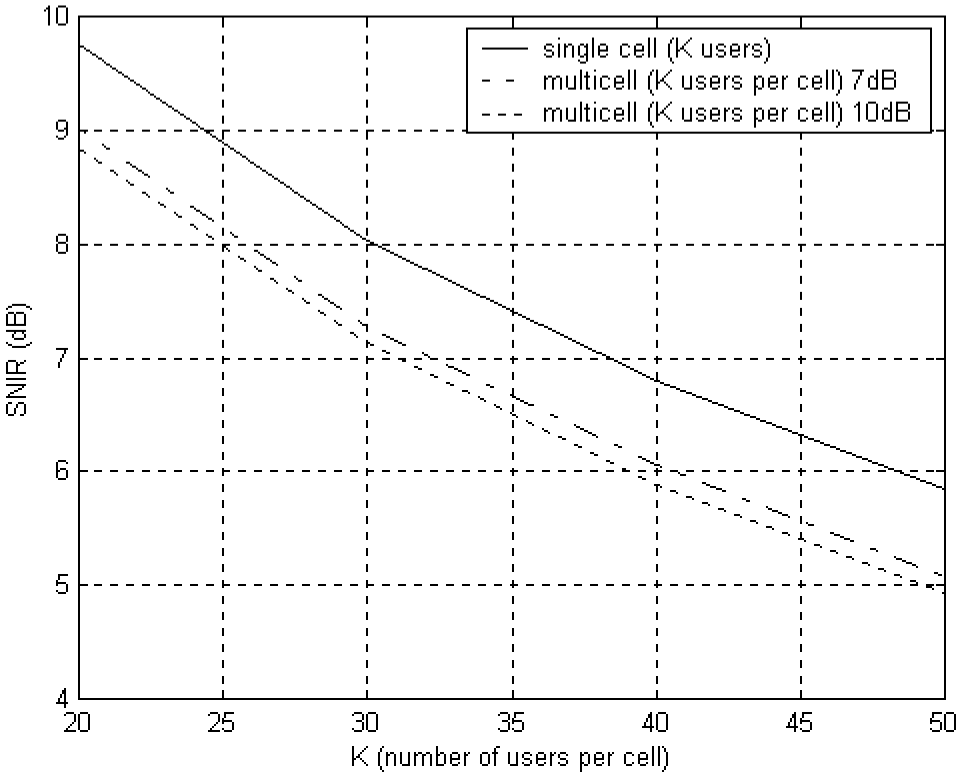

Figure 5. $SNIR$ versus K with $m = 0.8$, $p(g) = 0.99$, $s_e = s_{z_1} = 2dB$, $s_{z_2} = 7dB, 10dB$, $E_b / N_0 = 15dB$ and $N = 128$.

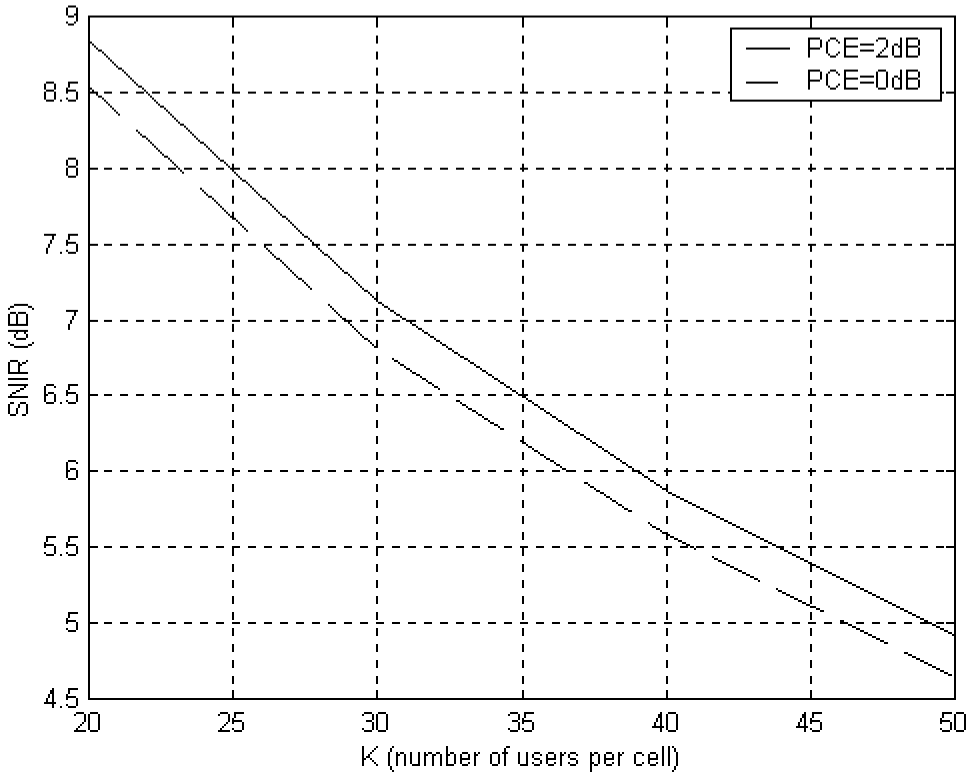

Figure 6. $SNIR$ versus K with $m = 1$, $p(g) = 1$, $s_e = 0dB, 2dB$, $s_{z_1} = 10dB, 2dB$, $s_{z_2} = 10dB$, $E_b / N_0 = 15dB$ and $N = 128$.

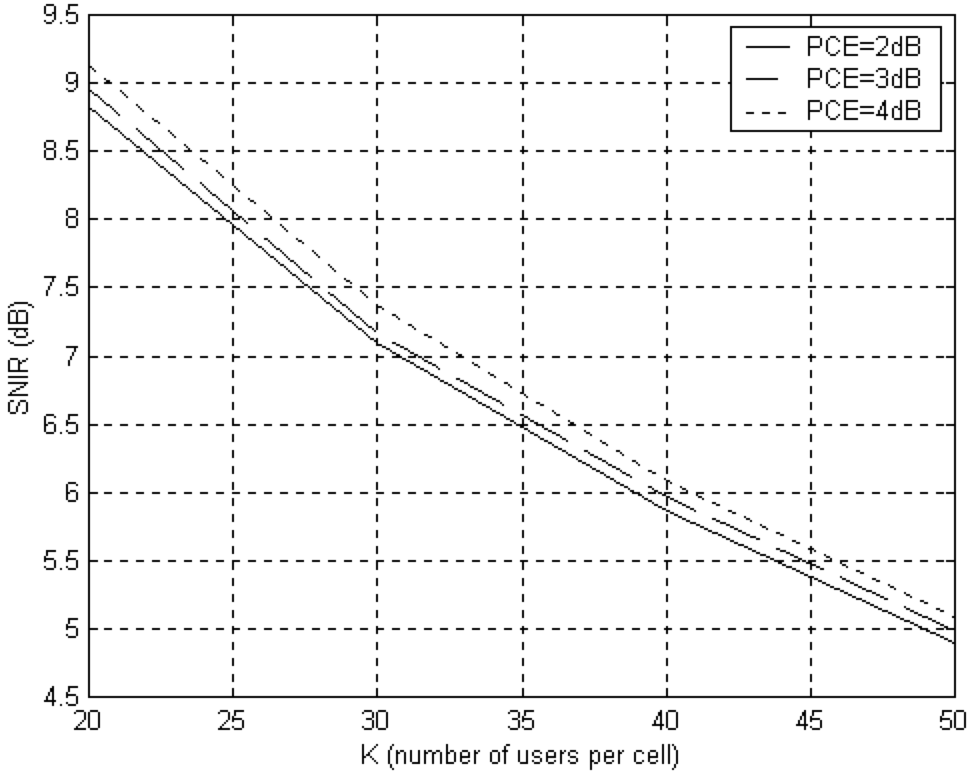

Figure 7. *SNIR* versus K with $m=1$, $p(g)=0.99$, $s_e = s_{z_1} = 2dB, 3dB, 4dB$, $s_{z_2} = 10dB$, $E_b / N_0 = 15dB$ and $N = 128$.

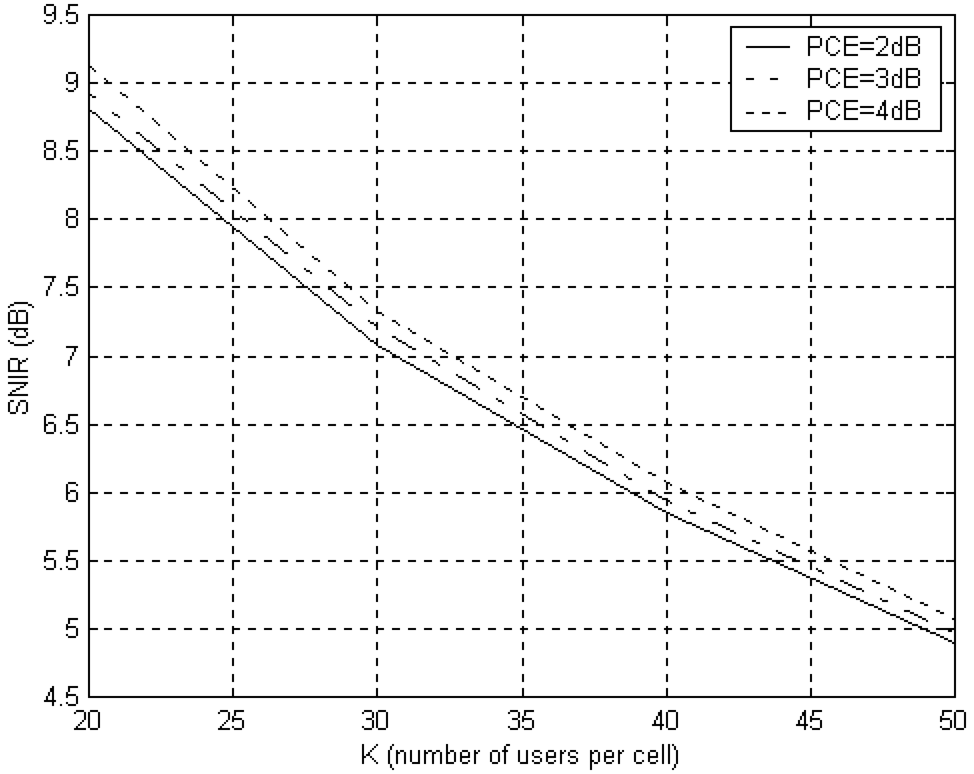

Figure 8. $SNIR$ versus K with $m = 1$, $p(g) = 0.9$, $s_e = s_{z_1} = 2dB, 3dB, 4dB$, $s_{z_2} = 10dB$, $E_b / N_0 = 15dB$ and $N = 128$.

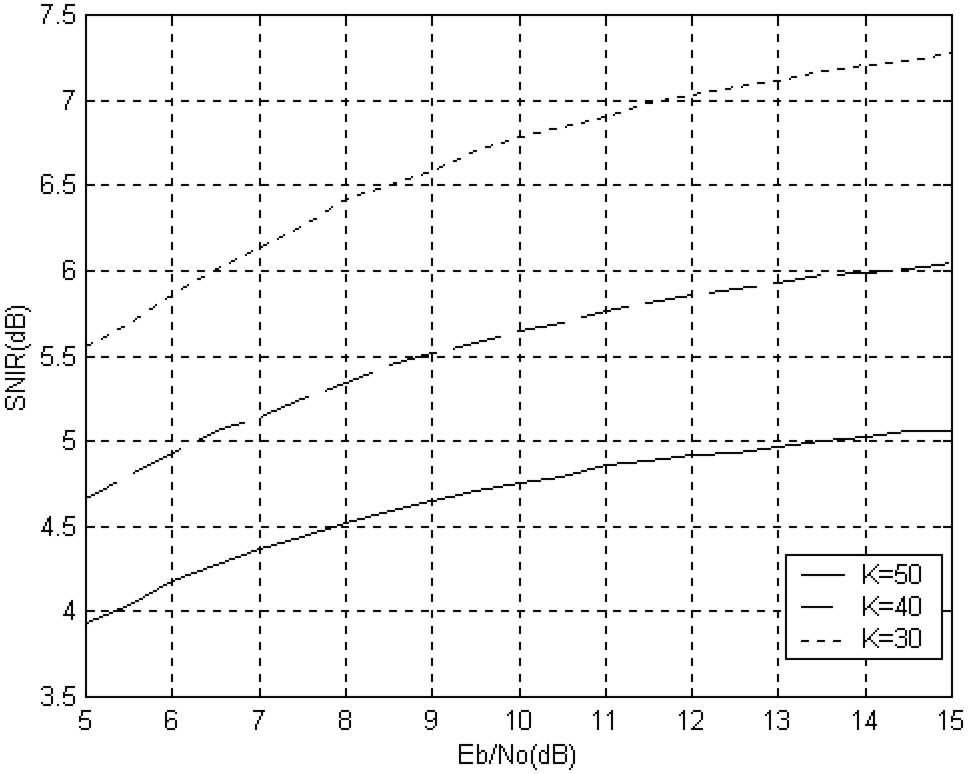

Figure 9. *SNIR* versus E_b / N_0 with $m = 1$, $p(g) = 0.99$, $s_e = s_{z_1} = 2dB$, $s_{z_2} = 7dB$, and $N = 128$, $K = 30,40,50$ users per cell.

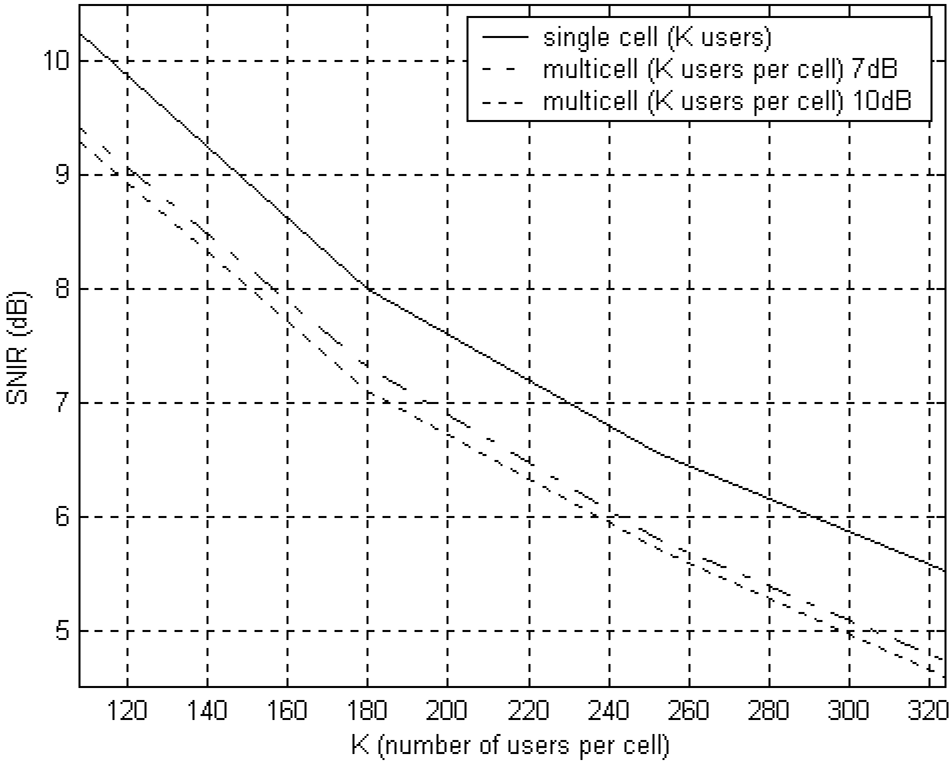

Figure 10. $SNIR$ versus K with $m = 0.8$, $p(g) = 0.99$, $s_e = s_{z_1} = 2dB$, $s_{z_2} = 7dB, 10dB$, $E_b / N_0 = 15dB$, $N = 128$ and 60^0 sectoring.

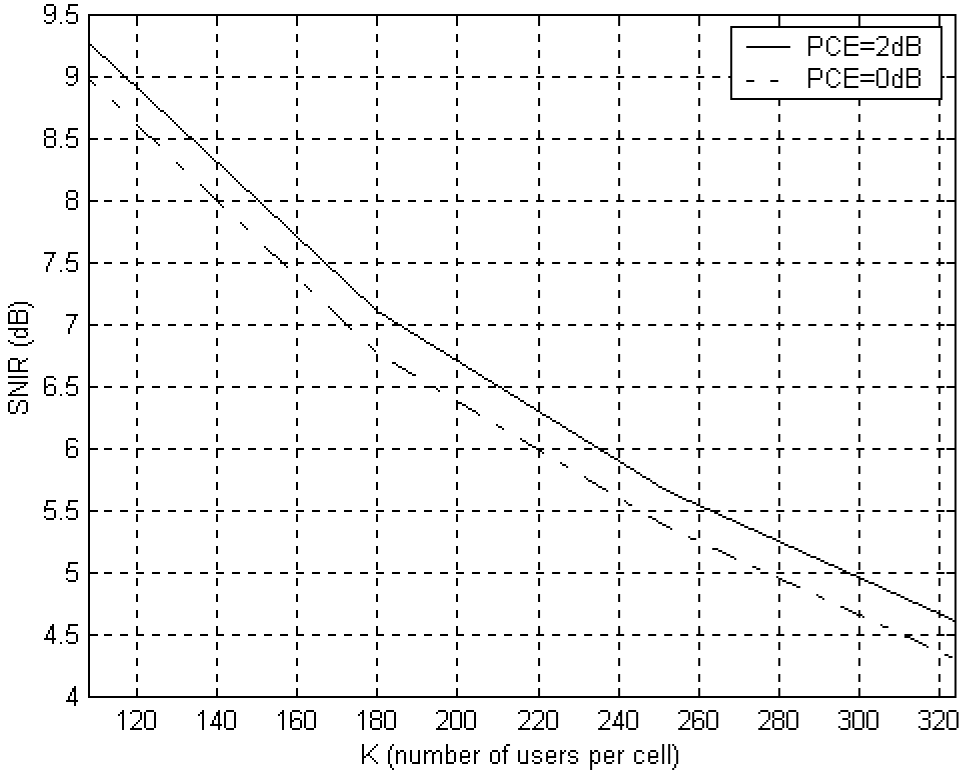

Figure 11. $SNIR$ versus K with $m = 1$, $p(g) = 1$, $s_e = 0dB, 2dB$, $s_{z_1} = 10dB, 2dB$, $s_{z_2} = 10dB$, $E_b / N_0 = 15dB$, $N = 128$ and 60^0 sectoring.

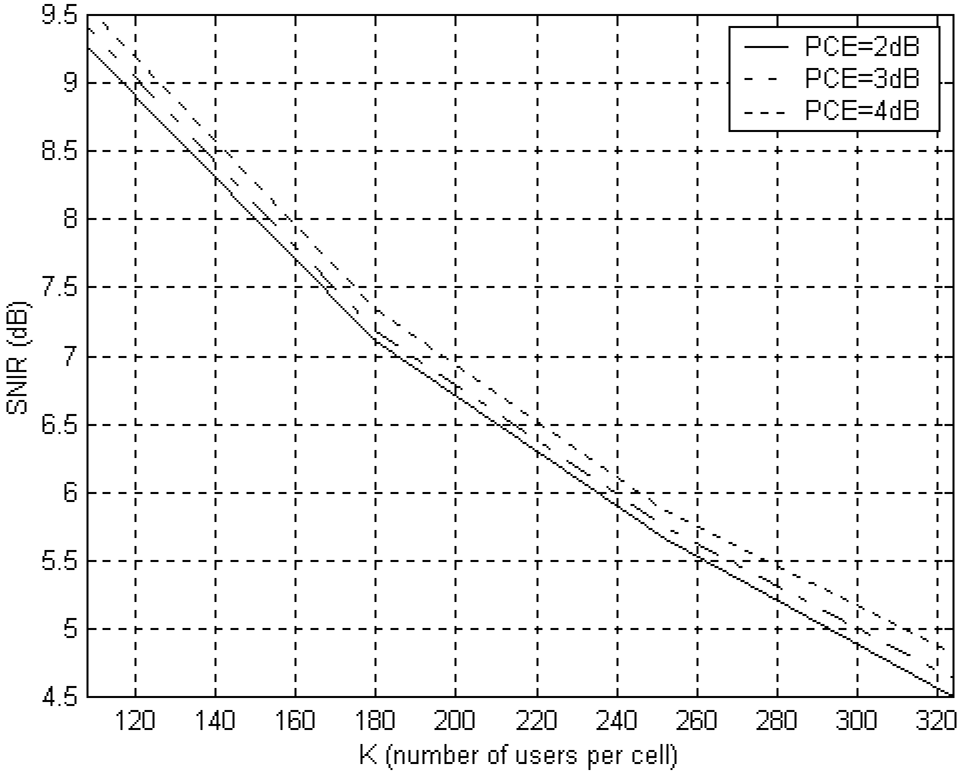

Figure 12. $SNIR$ versus K with $m = 1$, $p(g) = 0.99$, $s_e = s_{z_1} = 2dB, 3dB, 4dB$, $s_{z_2} = 10dB$, $E_b / N_0 = 15dB$, $N = 128$ and 60^0 sectoring.

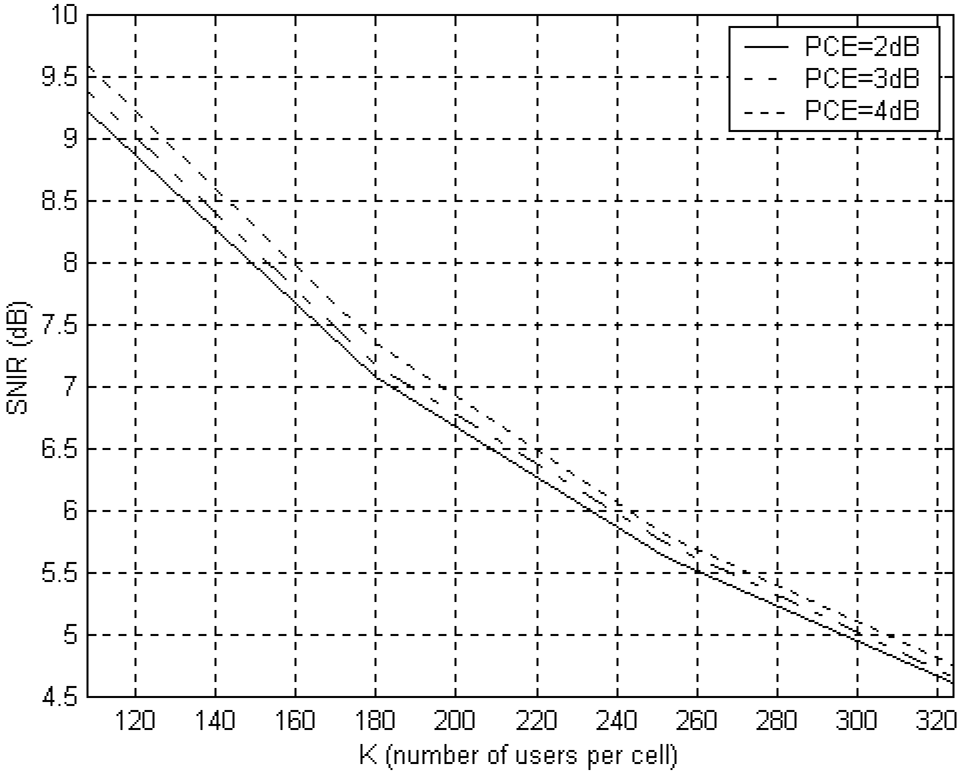

Figure 13. $SNIR$ versus K with $m=1$, $p(g)=0.9$, $s_e = s_{z_1} = 2dB, 3dB, 4dB$, $s_{z_2} = 10dB$, $E_b/N_0 = 15dB$, $N=128$ and 60^0 sectoring.

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V. CONCLUSIONS

In this thesis combined adaptive power and rate control in the reverse channel of a multicell CDMA cellular system over a Nakagami-Lognormal frequency selective fading channel are investigated. Conventional power control or perfect power control cannot be implemented in practice, so imperfect power control is considered.

The techniques of truncated power control, power and rate adaptation and truncated rate adaptation, provide a power gain over the conventional power control because they do not compensate for deep fading using large transmission power. Power gain translates to a reduction in interference, both intracell and intercell, and leads to a capacity increase because CDMA cellular systems are interference limited systems. Additionally, these techniques reduce the average transmit power of the mobile user, and as a result they prolong the battery life of the mobile phone.

Numerical results for truncated power control show that this technique results in a capacity gain for the system. As the truncation probability increases the system has better performance. Furthermore, it is also shown that as the standard deviation of the power control error that accounts for imperfect power control increases, the system performs poorer. In addition, concerning the Nakagami fading channel, it is shown that as the factor m increases, the system performs better.

Finally, it is shown that employing 60^0 sectoring, results in a system capacity increase by a factor of 6, due to the interference reduction.

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5. Dimitrios Nalmpantis
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