RICE UNIVERSITY

Resource Allocation in Wireless CDMA Multimedia Networks

by

Yile Guo

A Thesis Submitted
in Partial Fulfillment of the
Requirements for the Degree

Doctor of Philosophy

Approved, Thesis Committee:

Behnaam Aazhang, Chair
Professor in Electrical and Computer
Engineering

Edward W. Knightly
Assistant Professor in Electrical and
Computer Engineering

Joseph R. Cavallaro
Associate Professor in Electrical and
Computer Engineering

Peter Druschel
Assistant Professor in Computer Science

Houston, Texas
May, 1999

Resource Allocation in Wireless CDMA Multimedia Networks

Yile Guo

Abstract

In this thesis we developed a resource allocation framework for wireless code division multiple access (CDMA) networks that support multi-class traffic with different data rates and bit error rate requirements. We proposed a new resource allocation scheme using joint adaptive power control and antenna array multiuser receiver in multipath fading system. In this scheme both transmit power and receiver filter adapt to time-varying fading channel state. By dynamically assigning users appropriate transmit power and receiver filter, the scheme can guarantee users' diverse quality of service (QoS) requirements and significantly improve quality and capacity of the system. We derived theory for abstraction of bandwidth resource and characterization of system capacity for multi-class traffic in multipath fading system. Bandwidth resource allocated to a user can be abstracted as "effective bandwidth", determined by the user's source data rate and target bit error rate. Capacity in multipath fading system can be characterized by a theoretical bound. Simulations show that actual system capacity in multipath fading environment is close to the theoretical bound at large power constraint. The multirate multiuser receiver can achieve significantly larger capacity for users with higher source data rate and lower target bit error rate than conventional matched-filter receiver. The antenna array multiuser receiver can provide large capacity for users with higher signal-to-interference ratio requirement and achieve high bandwidth utility at lower power constraints. We also proposed a new call admission control scheme for CDMA cellular system that incorporates adaptive power control and antenna array multiuser receiver and supports multi-class traffic. The scheme is based on estimation of othercell interferenceand implemented distributively in each cell. The scheme can adapt to various traffic distribution. Capacity determined by the admission control agrees well with the actual system capacity in the simulation. The scheme can achieve high bandwidth utilization and guarantee QoS requirements of all the users.

This thesis is dedicated to my wife Florence,
without her enormous love, optimism, persistence, and support I would not have
come even close to what I have achieved today.

Acknowledgments

I would like to express deep gratitude to my thesis advisor Dr. Behnaam Aazhang, for his truly insightful thoughts that envisioned the topic of this thesis and guided me through the entire journey toward the final accomplishment of the work. His inspiration, encouragement, trust, and support are invaluable to me. After all, He is *the* best advisor that I can ever imagine having.

I would like to thank Dr. Edward Knightly, Dr. Joseph Cavallaro and Dr. Peter Druschel for being on my thesis committee, and for their contribution of precious time in providing suggestions, comments and questions that greatly helped clarifying issues and improving quality of the thesis.

I really enjoyed being part of Rice Wireless Research Group led by Dr. Aazhang and Dr. Cavallaro, and Rice Networks Group led by Dr. Knightly, and I thank my colleagues Dr. Chaitali Sengupta (currently with Texas Instruments), Dr. Raghavendra Madyastha (currently with Aware Inc.), Suman Das, Jin Lu, Andrew Sendonaris, Srikrishna Bhashyam, Denish Rajan, Gang Xu, Vishwas Sundaramurthy, Dr. Kang Lee (currently with Texas Instruments), Dr. Akbar Sayeed (currently with University of Wisconsin), Dr. Elza Erkip, Dr. Aria Nosratinia, Jinyu Qiu (currently with Microsoft Corporation), Tao Wu, Rahul Jain et al for their unconditional willingness in providing enlightening discussion, friendly assistance and productive collaboration.

I would like to thank my colleagues from Nokia Corporation Jorma Lilleberg and Ari Hottinen for their generous support and valuable advice. I would also like to thank my colleagues Steve Cable, John Jubin, Dr. Hersh Parekh, Phillip Laas, Kenneth Combs, Richard VanderMeulen in Rockwell International Corporation. The skills and knowledge I gained there had great influence on my thesis work and prepared me for pursuing future careers. The projects in the thesis are sponsored by Nokia Corporation, Rockwell International Corporation, Texas Instruments, Texas Advanced Technology Program, National Science Foundation, etc. The financial support from these sources is gratefully acknowledged.

I'm greatly indebted to my parents Zengshou Guo and Minjue Hu and my parents-in-law Zhong Huang and Ping Niu for their uncommonly deep understanding and strong support on my choices of pursuing advanced studies that culminated this thesis.

Finally I wish to extend my deepest gratefulness to my lovely wife Florence Fang Huang, who has been accompanying me each and every day during the mission, who has constantly inspired my desire to excel, and who has always been confident on my ability to succeed. Without her enormous love, optimism, persistence, and support I would not have come even close to what I have achieved today.

Contents

Illustrations

Chapter 1

Introduction

1.1 Motivation

Next generation wireless networks will provide a variety of multimedia services to transport voice, data, images, video, and other media, as Figure 1.1 shows. To enable these services it is essential that next generation wireless networks support multiple classes of traffic with diverse quality of service (QoS) requirements in terms of data rate, bit error rate, delay, throughput, etc. For example, voice traffic generally requires a data rate of 8 kbps and bit error rate (BER) less than 10^{-2} to 10^{-3}, while video traffic requires data rate of 64 kbps and up, with BER less than 10^{-6}. These are usually real time traffic which requires end-to-end delay to be less than 200 ms. On the other hand packet data traffic are non real time and usually there is no strict delay bound imposed on that. The packet data traffic requires a wide range of data rates (from less than 1 kbps to several Mbps) and error rate less that 10^{-6}. To provide users with improved QoS it is desirable for next generation wireless networks to have enhanced performance, in terms of higher data rate, lower BER, lower latency, and higher throughput. It is equally important for next generation wireless networks to have higher system capacity in order to meet the rapidly escalating demands on accessing the backbone networks from anywhere at any time.

One of the viable technologies to meet these challenges is code division multiple access (CDMA). There are three different multiple access schemes through which multiple users can share an allocated spectrum resource, as Figure 1.2 shows. In

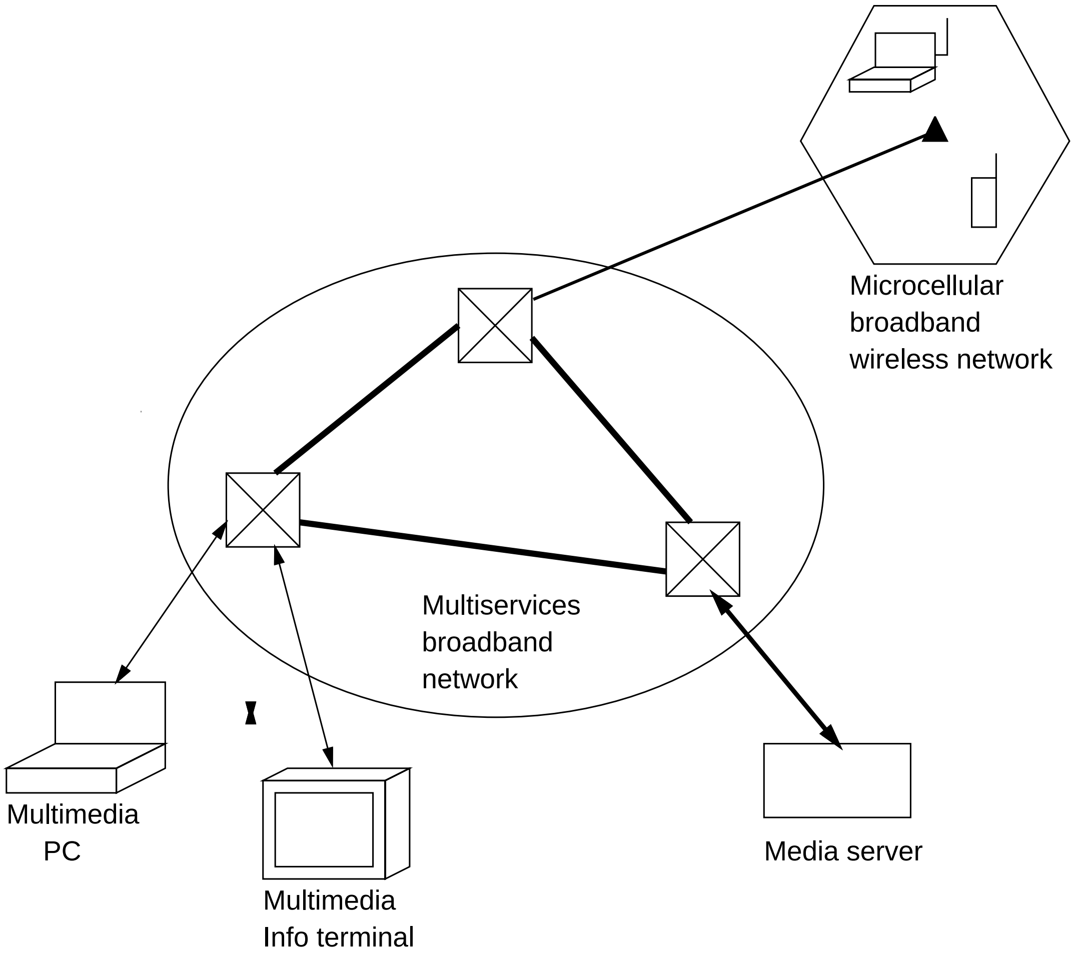

Figure 1.1 Wireless multimedia networks

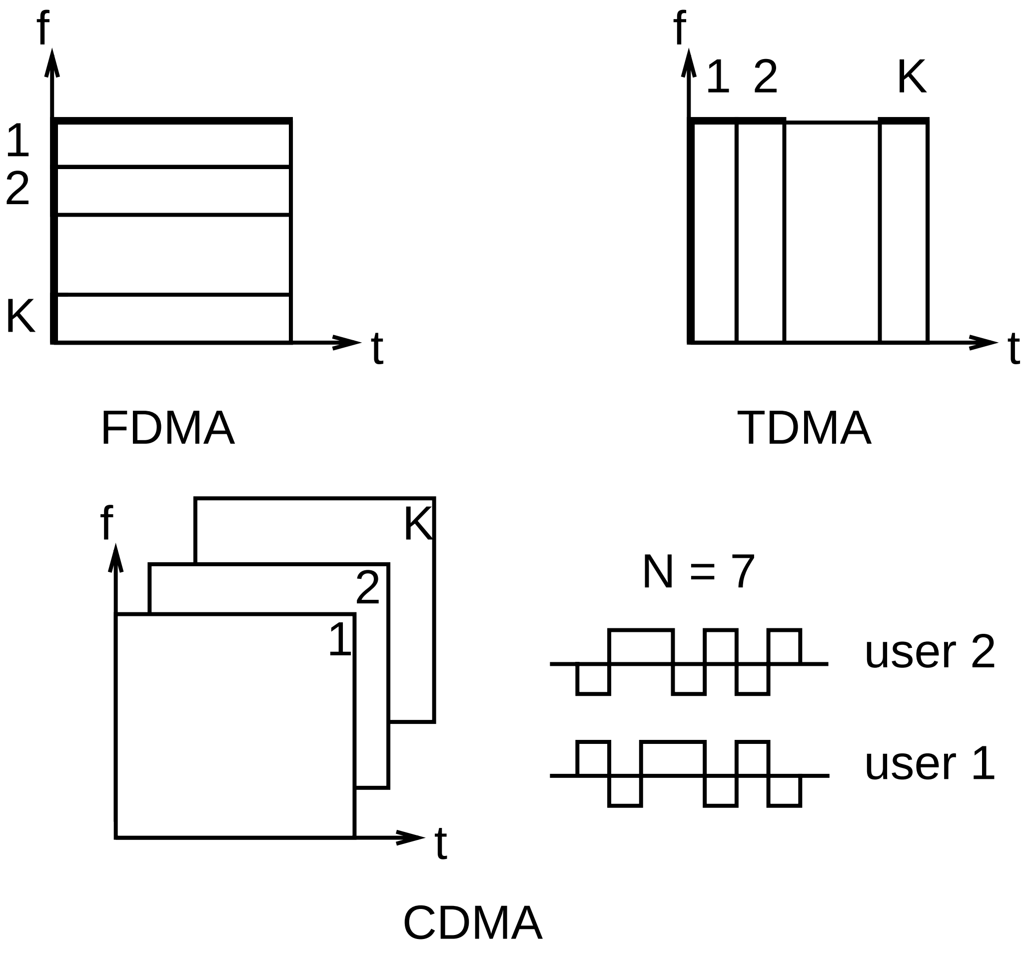

Figure 1.2 Multiple access schemes

frequency division multiple access (FDMA) scheme, each user is assigned a frequency slot in which the user transmits signal. In time division multiple access (TDMA) scheme, each user is assigned a time slot and the user transmits signal within its time slot. In contrast to FDMA and TDMA, in CDMA scheme each user is allowed to use the entire time-frequency space and users overlap each other in the time-frequency space. Each bit in the data stream is modulated or coded by a binary sequence called spreading signature or spreading code. Users are differentiated by their unique codes, which is nearly orthogonal and has small crosscorrelation. Compared to narrowband slotted schemes like FDMA and TDMA, the transmitted signal in CDMA is spreaded in both frequency (spread spectrum) and time (spread time). The large time-frequency product of CDMA signaling makes itself quite robust to fading in wireless channels. While narrowband signals concentrate on a particular time or frequency slot which may experience deep fading and severe performance degradation, CDMA signal energy is distributed among time-frequency slots throughout the space which experience independent fading. Since the probability that all these time-frequency slots experience deep fading is quite small, by combining the received signals of these slots in an optimal way a much better performance is achieved. This is one form of so called diversity techniques.

In CDMA systems the spreading sequences of different users are usually not mutually orthogonal due to the asynchronous transmission, the multipath fading channel, and the limitation on the number of available orthogonal codes. This causes multiple access interference (MAI) when many users access the allocated spectrum simultaneously in a CDMA system. A direct result of that is the capacity vs. quality tradeoff, i.e. as more and more users access the spectrum simultaneously the performance of each user's communication link deteriorates. In order to maintain the link quality above certain specified level, it is necessary to limit the number of users accessing the spectrum at the same time. Therefore capacity of CDMA system is said to be limited by multiple access interference, or *interference limited*.

Current CDMA systems (e.g. IS-95) use a conventional matched filter receiver structure that treats other user's signal as noise and simply correlates the received signal with desired user's spreading codes. While easy to implement, this receiver suffers from performance degradation caused by severe multiple access interference when there are a large number of users accessing the spectrum. To improve the performance and capacity it is desirable to apply so called "performance enhancing" techniques in the next gereration wireless networks. Two performance enhancing techniques in European and Japan's third generation (3G) systems standard are advanced receiver structures and smart antenna arrays. Advanced receiver structures like multiuser receiver and interference cancellation exploit structure in other users' signaling to mitigate or cancel the multiple access interference. Smart antenna arrays jointly process signals received from multiple antennas to enhance the desired user's signal and reduce interference from other users. While there exist many works that propose different multiuser receiver and antenna array structures, most of them focus on demonstrating the performance improvement in the physical layer in terms of lower bit error rate. They generally assume either no power control or some simple fixed power control scheme in which all the users' received power at the receiver is kept the same. These works are usually limited to single class traffic with same data rate and target bit error rate. Issues like power and bandwidth resource allocation and system capacity for multi-class traffic are still unclear.

1.2 Problem to Solve

Wireless CDMA Communications has been traditionally viewed as a physical-layer subject. Due to the unique feature that in a CDMA system users are sharing the allocated bandwidth and competing for the bandwidth by adjusting their power level at the receiver, the problem can also be formulated from a resource allocation point of view. The objective of resource allocation in wireless networks is to decide how to allocate resources such as power, bandwidth and channel such that quality of service requirements of all the users' can be satisfied. The resource allocation issues in CDMA networks include those related to three different problems:

- **power control, receiver structure, abstraction of bandwidth resources, and characterization of system capacity in multi-class traffic system.** The goal is to guarantee their QoS requirements in terms of data rate and bit error rate.

- packet access control and scheduling of heterogeneous traffic such as constant bit rate (CBR), variable bit rate (VBR), packet data, etc. The goal is to guarantee their QoS requirements in terms of delay and throughput.

- **call admission control (CAC)** and handoff control **in cellular systems**. The goal is to guarantee QoS at the call level.

In this thesis we focus on solving the resource allocation problem in multi-class traffic system. The solution to this problem builds a foundation on which one can develop schemes like packet access control and scheduling policy. We also provide a solution to the call admission control problem in CDMA cellular systems. Our objective is to establish a resource allocation framework for CDMA networks that can

- allocate power and bandwidth resource to multiple classes of traffic.

- guarantee diverse QoS requirements in terms of data rate and bit error rate.
- incorporate performance enhancing techniques such as multiuser receiver and antenna array.
- allow a simple abstraction of bandwidth resource allocated to each user.
- provide a clear format to characterize system capacity.
- control the new call admission in adpative to traffic distribution in cellular networks.

This problem is challenging because of the difficulties associated with supporting multimedia applications in wireless communications environment:

- The wireless channel is time varying due to the multipath fading effect, the resource allocation scheme needs to be *adaptive*.
- The radio bandwidth is a scarce resource, the resource allocation scheme needs to be *efficient*.
- To support multiple classes of traffic with different data rates and bit error rate requirements, the resource allocation scheme needs to be *flexible*.
- Due to the limited power available in the handset, the resource allocation scheme should *minimize transmit power*.
- Due to the significant multiple access interference in CDMA systems, it is desirable that the resource allocation scheme *incorporates performance enhancing techniques*.

Most existing multiuser receiver and antenna array schemes do not assume power control. While system performance is improved, users' QoS requirements cannot be guaranteed. On the other hand, iterative power control have been used in systems with conventional matched-filter system. Users' QoS requirements can be guaranteed but they suffer from lower quality and capacity due to multiple access interference. Joint power control and multiuser receiver schemes have been proposed in which users' transmit power and receiver filter are iteratively updated to suppress the multiple access interference and achieve required SIR. These schemes can improve quality and capacity of the system and guarantee users' QoS requirements. Recent works have focused on understanding capacity of such systems. Using theorem derived in analytical format simple characterization of system capacity is obtained. The results are asymptotic in nature and apply to system with infinite number of users. These works are limited to Gaussian channel which is unrealistic in wireless communication environment. They are for single cell system supporting single data rate, using single antenna receiver, and with infinite number of users.

1.3 Overview of the Thesis

In this thesis we present a solution to the resource allocation problem described in the previous section. We developed a new resource allocation scheme for wireless CDMA networks using **adaptive** power control and **antenna array** multiuser receiver in **multipath fading** channel. Our approach is that both transmit power and receiver filter adapt to time-varying fading channel state. By dynamically assigning users appropriate transmit power and receiver filter, the scheme can support multi-class traffic with **multiple data rates** and target bit error rate and guarantee their diverse QoS requirements. We derived theory for abstraction of bandwidth resource and characterization of system capacity in multipath fading environment. Our approach is to derive a theoretical bound on capacity analytically, and use simulation to find out actual system capacity. The results are applicable to system with **finite** number of users. We also proposed an call admission control scheme for CDMA **cellular system** using adaptive power control and antenna array multiuser receiver.

Multiuser receiver is one of the promising techologies to enhance the performance and capacity of current CDMA systems by mitigating multiple access interference. Multiuser detection for multirate CDMA communications where multiple users with different data rates coexist has been proposed. These works focus on demonstrating the performance improvement in the physical layer in terms of lower bit error rate. They usually assume either no power control or some simple fixed power control scheme and do not have a way to control the bit error rate. In Chapter 3 we study resource allocation and capacity of CDMA system using multiuser receiver to support multiple classes of traffic with different data rates and quality of service requirements. We propose a resource allocation scheme applying joint adaptive power control and multiuser detection. A multirate multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each symbol is proposed for multirate CDMA system. It is combined with adaptive power control based on target SIR to support traffic with different bit error probability (BER) requirements. A theoretical bound is derived to characterize capacity of multi-class CDMA system using the multiuser receiver. Simulations are carried out to study the actual system capacity in a multipath fading environment.

Antenna array or space-time processing can improve performance, coverage and capacity of wireless communication systems. In most of previous works various antenna array receivers are proposed and performance improvement in the physical layer in terms of lower bit error rate are demonstrated. They generally assume either no power control or some simple fixed power control scheme and consider only single class traffic with same data rate and bit error rate. In Chapter 4 we study resource allocation and capacity of CDMA system using antenna array multiuser receiver to support multiple classes of users with different quality of service requirements. We propose a resource allocation scheme applying joint adaptive power control and antenna array multiuser detection. An antenna array multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each user is proposed. It is combined with adaptive power control based on target SIR to support users with different bit error probability (BER) requirements. A theoretical bound is derived to characterize capacity of CDMA system using the antenna array multiuser receiver. Simulations are carried out to study the actual system capacity in a multipath fading environment.

Due to the statistical multiplexing inherent in CDMA system there is a tradeoff between the system capacity and the level of quality of service. In order to guarantee the quality of service for all the traffic in a cellular system, call admission control (CAC) must be applied to control the number of users in each cell such that an appropriate level of communication quality can be maintained. Previous works on admission control in CDMA systems are interference-based or SIR-based. They are applicable only to systems with conventional single antenna receiver which treats other users' signal as noise, with fixed power control in which all the users' received power at the base station are kept the same, and support single-class traffic. In Chapter 5 we propose a new admission control scheme for CDMA cellular system using adaptive power control and antenna array multiuser receiver and supports multiple classes of traffic. A relation of cell capacity and other-cell interference level is first established. Then admission control is implemented in each cell based on estimation of other-cell interference. Performance of the CAC scheme is evaluated by comparing the cell capacity determined by the admission control and the actual system capacity in the simulation.

1.4 Review of Related Works

This thesis focuses on wireless multimedia networks based on CDMA technology. Due to its technical advantage in various aspects, like robustness to fading, flexibility in capacity and quality tradeoff, inherent statistical multiplexing of heterogeneous traffic, etc., CDMA has been selected as the major air interface of the third generation systems standards for International Mobile Telecommunication at year 2000 (IMT-2000). These standards include wideband CDMA proposed by Europe [1], cdma2000 proposed by U.S. [2], wideband CDMA proposed by Japan [3], Time-Division Synchronous CDMA proposed by China [4], and Global CDMA I/II proposed by Korea [5]. Overview of the radio, network, service and regulation aspects of IMT-2000 are given in [6, 7, 8, 9]. On the other hand, the currently successful commercial CDMA systems are based on a family of air interface standards called cdmaOne, including IS-95 for cellular system [10] and J-STD-008 for PCS system [11]. The IS-95 based CDMA systems are discussed in [12, 13, 14, 15, 16].

The resource allocation scheme proposed in this thesis uses single antenna and antenna array multiuser receiver. In order to detect the symbol sequences, it is necessary for the receiver to estimate the channel response, in the form of effective spreading signatures and effective spatial-spreading signatures. This is a challenging problem due to the multipath fading channel and multiple access interference in CDMA system. The problem is addressed in [17, 18]. In the thesis it is assumed that channel estimation is implemented in high accuracy and the receiver has the perfect knowledge of the channel response.

The resource allocation scheme in the thesis uses adaptive power control. Power control for cellular radio systems are studied in [19, 20]. Power control for a multimedia CDMA wireless system is proposed in [21]. Power control in macrodiversity

CDMA networks is studied in [22]. Joint power control and handoff for cellular CDMA system are studied in [23, 24]. All these works are for CDMA systems using conventional matched filter receiver.

Multiuser receiver or multiuser detection for CDMA systems in additive white Gaussian noise (AWGN) and fading channels have been studied extensively [25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37]. In particular, multiuser detection for multirate CDMA systems are studied in [38, 39, 40, 41, 42]. Most of these works are aimed at demonstrating the superior capability of multiuser detection in combating so called near-far problem, therefore assume no power control in the system. It is a long time belief that since multiuser detection is near-far resistant there is no need for power control. This is challenged in [43], which argues that adaptive power control is still necessary for CDMA systems using multiuser receivers. In [44] adaptive power control and multiuser detector are combined in a power control algorithm which iteratively updates the transmitter powers and receiver filter coefficients of the users. The works in [45, 46, 47, 48, 49, 50] focus on understanding the capacity of CDMA systems with power control and multiuser receivers. It is shown that using concepts like effective interference and effective bandwidth, the capacity of a single cell for several important receivers can be characterized in a simple format. While these works are based on elegant mathematical theorem and the results can be derived analytically, they are asymptotic in nature and apply only to systems where number of users goes to infinity. All the above works that use joint power control and multiuser detection are for CDMA systems in AWGN channel. They have not considered CDMA systems supporting multiple data rates or with antenna array receivers. On the other hand, the resouce allocation scheme developed in this thesis uses a new approach in which both the transmit power and receiver filter adapt to the time-varying channel state and works for CDMA systems in multipath fading channel. Our scheme can support multiple classes of traffic with different data rates and guarantee their diverse QoS requirements in terms of target bit error rate. Our scheme incorporates both single antenna and antenna array multiuser receivers in CDMA systems. Capacity of multiclass traffic CDMA system using adaptive power control and multiuser receiver is studied in [51, 52]. Our approach is to establish an upper bound on system capacity which can be proved analytically. Then simulations in multipath fading environment are carried out to study the actual system capacity and the results are compared with the theoretical bound. Our results are valid for systems with finite number of users.

Error correction coding with varible code rate is used in our scheme to provide different levels of protection to users with different bit error rate requirements. A description of these codes and their performance can be found in [53, 54]. In our scheme multiple data rates are supported by varying spreading factors, i.e. varible spreading or multi-processing-gain. Other multirate schemes include multi-modulation, multicode, multi-chip-rate, etc. These schemes are discussed in [53].

There exist significant amount of research works on various smart antenna array or space-time processing technologies to improve performance, coverage and capacity of wireless communication systems. For a review of these works see [55, 56, 57] and the references therein. Antenna array or antenna diversity techniques for wireless communication systems not specific to CDMA are studied in [58, 59, 60, 61, 62]. Antenna arrays for CDMA systems are studied in [63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74]. In most of these works various antenna array receivers are proposed and performance improvement in the physical layer in terms of lower bit error rate are demonstrated. They generally assume either no power control or some simple fixed power control scheme and consider only single class traffic with same data rate and bit error rate. Joint optimal power control and beamforming using antenna arrays are proposed in [75, 76] for general wireless systems. Power control and space-time diversity 2D RAKE receiver for CDMA systems are proposed in [77]. These works are limited to single class traffic as well. There have not been a clear format for characterizing system capacity. In the resource allocation scheme developed in this thesis we propose a new approach using adaptive power control and antenna array multiuser receiver for CDMA systems in multipath fading channel. This receiver jointly processes received signal vectors sampled at chip rate from multiple antennas and maximizes the signal-to-interference ratio for each user. It is combined with adaptive power control based on target SIR to support multi-class traffic with different bit error rate requirements. Capacity of CDMA system using adaptive power control and antenna array multiuser receiver is studied in [78]. A theoretical bound is derived to characterize system capacity in a simple format. Simulations in multipath fading environment are carried out to study the actual system capacity and the results are compared with the theoretical bound.

In the thesis we consider both single cell and cellular CDMA systems. For single cell CDMA system we usually model received power in terms of signal-to-thermal noise ratio (SNR) in the simulation. For cellular CDMA system where multiple base stations are involved, we need to model the handset transmit power and propagation loss. The propagation model we use in the thesis are described in [79].

We proposed in the thesis a new call admission control scheme for cellular CDMA system using adaptive power control and antenna array multiuser receiver. Admission control in cellular PCS networks is studied in [80]. Existing works on call admission control for CDMA systems [81, 82, 83] are interference-based or SIR-based. They are applicable only to systems with conventional single antenna receiver, with fixed power control, and support single-class traffic. Our admission control scheme is based on estimation of other-cell interference and works for cellular CDMA system using adaptive power control and antenna array multiuser receiver and supports multi-class traffic. It is noticed that user mobility and integrated voice/data traffic are not modeled in this thesis, although the proposed scheme is extendable to include these factors. Admission policies for integrated voice/data traffic in CDMA networks is studied in [84]. Call admission algorithms for wireless networks that consider user mobility are studied in [85, 86, 87].

In this thesis we focus on solving the resource allocation problem involving power control, receiver structure, abstraction of bandwidth resources and characterization of system capacity for multi-class traffic system. We also proposed an admission control scheme for cellular system. The resource allocation issues involving packet access control and scheduling of heterogeneous traffic such as CBR, VBR and packet data are not addressed in the thesis. The access control and packet scheduling for supporting intergrated services in TDMA-based wireless networks are studied in [88, 89, 90, 91]. The access control and packet scheduling for wireless CDMA systems supporting integrated services are studied in [92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102]. These works do not incorporate performance enhancing techniques that are essential for improving capacity and quality of next generation wireless systems. It is an interesting research topic to develop a packet access control and scheduling scheme that can support integrated services in wireless CDMA systems incorporating performance enhancing techniques like multiuser receivers and antenna arrays. Our results on resource allocation for multi-class traffic can serve as a starting point for solving this problem.

Chapter 2

CDMA System Model

2.1 Multi-class Traffic CDMA System

We consider a direct-sequence CDMA system that supports multiple classes of traffic with different data rates and bit error rate requirements, as illustrated in Figure 2.1. There are K users in the CDMA system, each transmitting information bits with source data rate of R_k and bit error rate requirement of P_k^*. The transmitter consists of variable rate error correction coding, variable spreading and transmit power control. Multiple symbol rates are supported by varying the spreading factor while maintaining fixed chip rate and symbol alphabet, as shown in Figure 2.2. The lowest symbol rate in the system is said to be the basic rate, denoted as R, and the symbol period for the basic rate is termed as basic symbol period. User k transmits M_k symbols in a basic symbol period, where M_k is an integer. This corresponds to an M_k-fold increase in symbol rate of user k at M_kR. The spreading factor for user k is N/M_k, where N is the spreading factor corresponding to the basic rate. Error correction coding with variate rate is used to provide different levels of protection for the source information bits. User k can choose a coding rate r_k, and source data rate and symbol rate are related by $R_k/r_k = M_kR$. The modulated signal of user k is transmitted at power p_k.

The received signals are jointly demodulated by a single antenna or antenna array multiuser receiver, followed by separate decoding for each user. The signal-to-interference ratio of user k's demodulated signal is γ_k, while the bit error rate of user k's decoded information bits is P_k. To maintain bit error rate of user k below

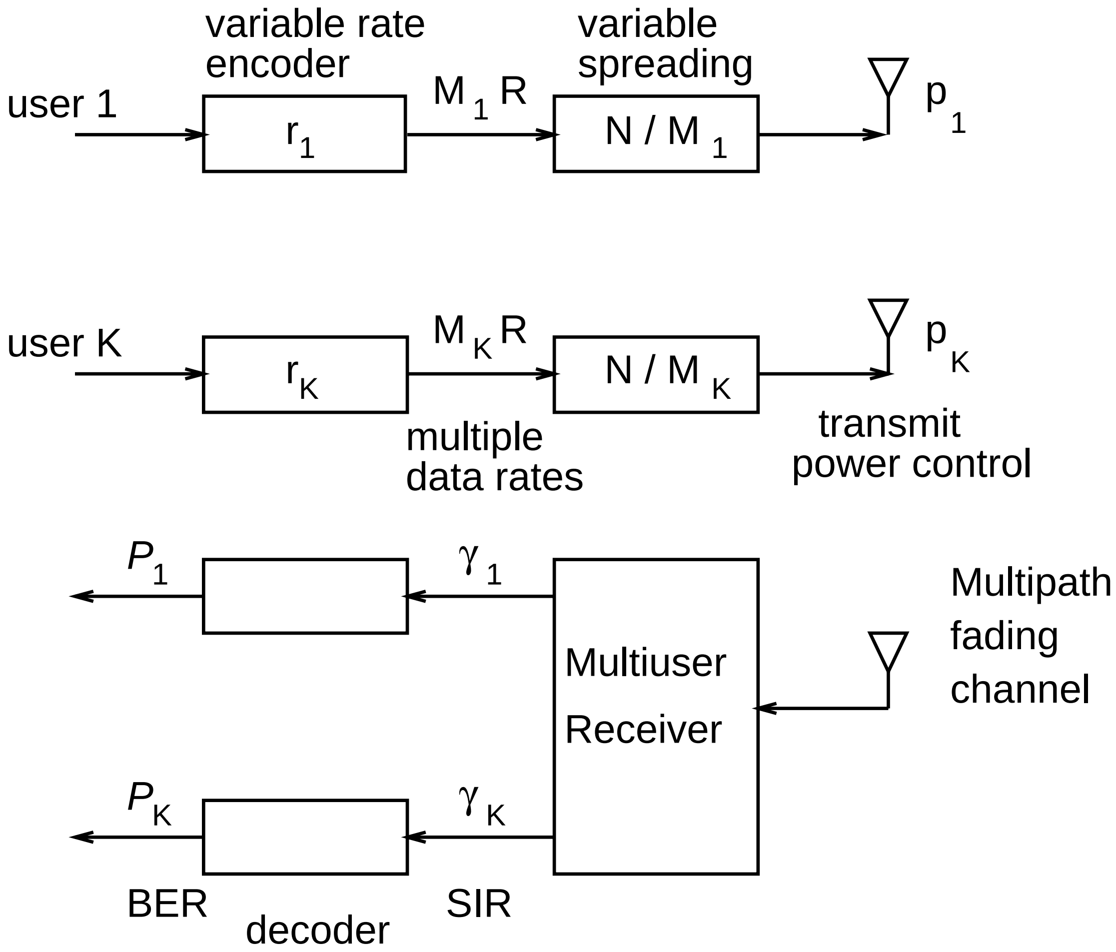

Figure 2.1 Multi-class traffic CDMA system

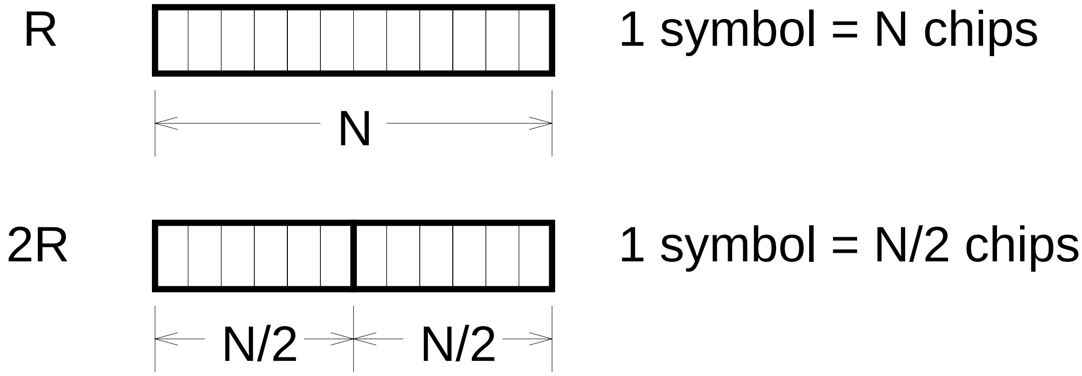

Figure 2.2 Multirate scheme: variable spreading

a required level of P_k^*, it is necessary to keep SIR of user k higher that certain value γ_k^*. The required SIR γ_k^* is decided by the target bit error rate P_k^*, the coding rate r_k, and distribution of γ_k. The adpative power control algorithm adjusts the transmit power p_k such that the SIR at the receiver exceeds or equal to the required SIR for all the user, $\gamma_k \geq \gamma_k^*$.

2.2 Multipath Fading Channel Model

In this thesis we use a multipath fading channel model for both single antenna and antenna array multiuser receiver. In a CDMA cell multiple mobile users at different locations communicate with a base station equipped with single antenna or antenna array receiver, as shown in Figure 2.3. Each user's transmitted signal travels through multiple paths due to the reflection and diffraction from nearby objects. The signals through multiple paths arrive at receiver with different amplitude, phase, delay and angle of arrival (AOA). We assume there are L resolvable paths for a certain user. The amplitude and phase of the lth path is described by a complex coefficient denoted as α_l. Since each path is a combination of many unresolvable subpaths which may add up constructively or destructively, α_l is assumed to be a complex random variable. The amplitude of α_l is Rayleigh distributed and the phase of α_l is uniformly distributed in $[0, 2\pi)$. This is so called Rayleigh fading model. The delay of the lth path is assumed to be multiples of the chip duration and expressed in terms of number of chips d_l. These are illustrated in Figure 2.4.

The angle of arrival of the lth path is denoted as θ_l, as shown in Figure 2.5. Due to the reflection and diffraction effect we assume that θ_l are uniformly distributed within $[\theta - \theta_d/2,\ \theta + \theta_d/2]$, where θ is the AOA of the user and θ_d is the dispersion angle of the multipaths.

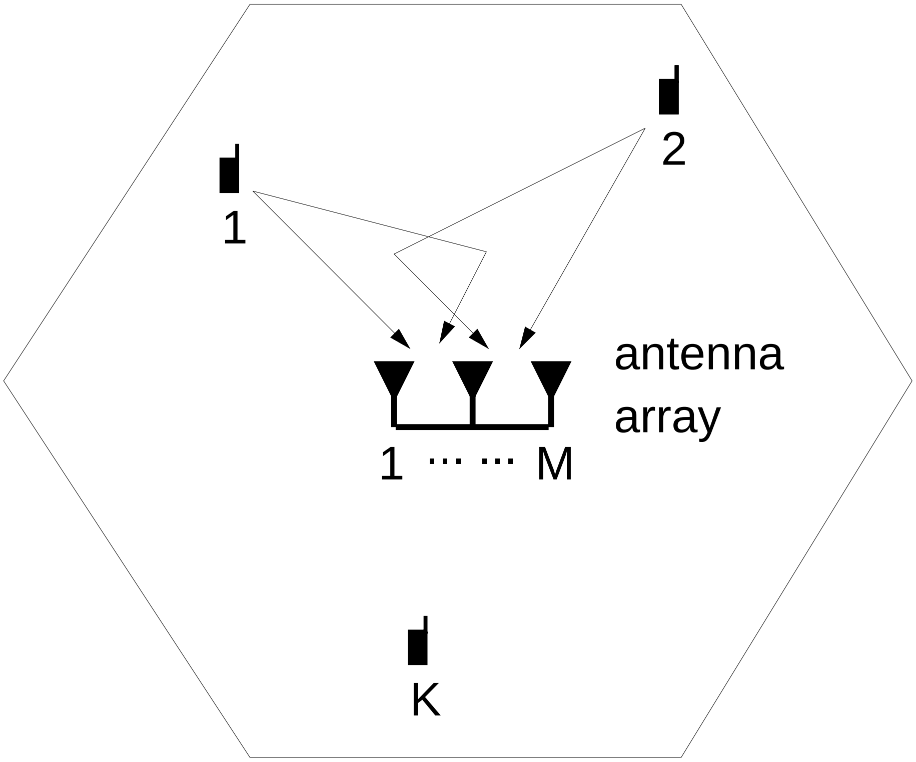

Figure 2.3 A CDMA cell with antenna array receiver

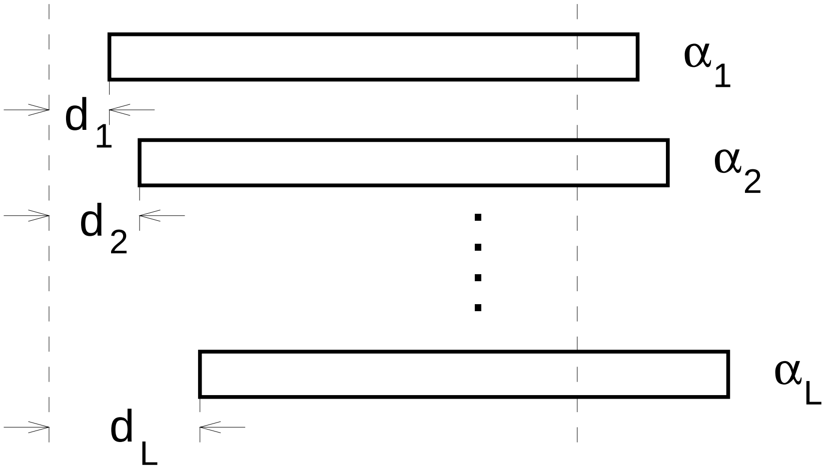

Figure 2.4 Multipath channel model: coefficient and delay

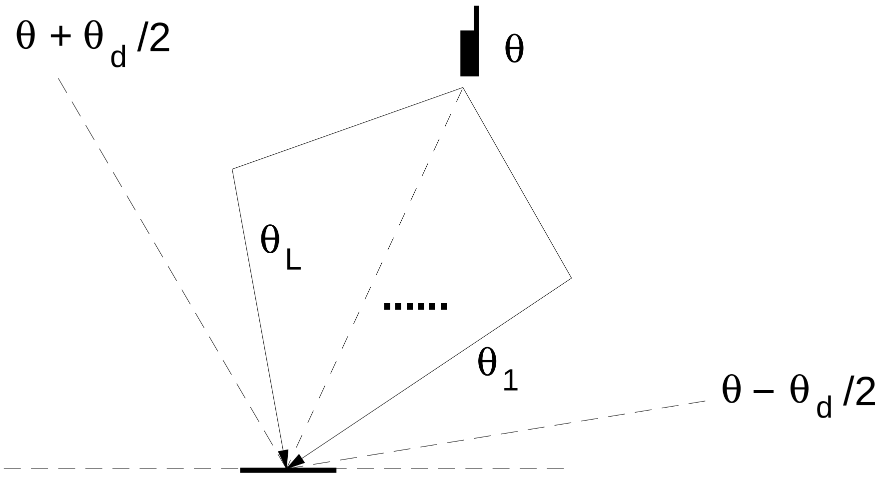

Figure 2.5 Multipath channel model: angle of arrival

Chapter 3

Multirate CDMA System with Multiuser Receiver

Next generation wireless networks will support multiple classes of traffic with different quality of service (QoS) requirements such as date rate and bit error rate. Multiuser receiver is one of the promising techologies to enhance the performance and capacity of current CDMA systems by mitigating multiple access interference. Multiuser detection for multirate CDMA communications where multiple users with different data rates coexist has been proposed. These works focus on demonstrating the performance improvement in the physical layer in terms of lower bit error rate. They usually assume either no power control or some simple fixed power control scheme and do not have a way to control the bit error rate. In this chapter we study resource allocation and capacity of CDMA system using multiuser receiver to support multiple classes of traffic with different data rates and quality of service requirements. We propose a new resource allocation scheme applying joint adaptive power control and multiuser detection in multipath fading channel. Our approach is that both transmit power and receiver filter adapt to the time-varying fading channel state. A multirate multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each symbol is proposed for multirate CDMA system. It is combined with adaptive power control based on required SIR to support traffic with different bit error probability (BER) requirements. A theoretical bound is derived to characterize capacity of multi-class CDMA system using the multiuser receiver. Simulations are carried out to study the actual system capacity in a multipath fading environment. The rest of the chapter is organized as follows: Section 3.1 describes the CDMA system model. In Section 3.2 a theoretical bound is derived for characterizing capacity of the multirate system. Section 3.3 simulations in multipath fading environment are described. In Section 3.4 numerical results and discussion are presented. The main results are summarized in Section 3.5. This chapter focuses on CDMA system using single antenna multiuser receiver. System using antenna array multiuser receiver are discussed in Chapter 4.

3.1 System Description

We consider a direct-sequence CDMA system with BPSK modulation and coherent detection, and focus on synchronous transmission in the uplink. Multiple data rates are supported by varying the spreading factor while maintaining fixed chip rate and symbol alphabet. The lowest symbol rate in the system is said to be the basic rate, and the symbol period for the basic rate is termed as basic symbol period. User k transmits M_k symbols in a basic symbol period, where M_k is an integer. This corresponds to an M_k-fold increase in data rate for user k. The received signal vector sampled at chip rate in a basic symbol period can be written as

$$\mathbf{r} = \sum_{k=1}^{K} \sum_{i_k=1}^{M_k} A_{k,i_k} b_{k,i_k} \mathbf{a}_{k,i_k} + \mathbf{n}, \tag{3.1}$$

where A_{k,i_k} and b_{k,i_k} are the received amplitude and the transmitted bit for the $i_k th$ symbol in the basic symbol period of user k respectively, and $\mathbf{a}_{k,i_k}$ is defined as

$$\mathbf{a}_{k,i_k} \equiv \sum_{l=1}^{L_{k,i_k}} \alpha_{k,i_k,l} \mathbf{s}_{k,i_k,l}, \tag{3.2}$$

in which L_{k,i_k} is the number of paths associated with the $i_k th$ symbol of user k, $\alpha_{k,i_k,l}$ is the complex coefficient associated with path l of the $i_k th$ symbol of user k, and $\mathbf{s}_{k,i_k,l}$ contains the chip matched-filter output samples of the spreading waveform of user k at the delay of the lth path of the $i_k th$ symbol. One can think of $\mathbf{a}_{k,i_k}$ as the "effective spreading signature" of the $i_k th$ symbol of user k. There are $\tilde{K} \equiv \sum_{k=1}^{K} M_k$ symbols in a basic symbol period. In the receiver a filter with coefficients $\mathbf{c}_{k,i_k}$ is used to demodulate the $i_k th$ symbol of user k and the receiver statistic is given by

$$\mathbf{c}_{k,i_k}^H \mathbf{r} = A_{k,i_k} b_{k,i_k} \mathbf{c}_{k,i_k}^H \mathbf{a}_{k,i_k} + \sum_{(k',i'_k)\neq(k,i_k)} A_{k',i'_k} b_{k',i'_k} \mathbf{c}_{k,i_k}^H \mathbf{a}_{k',i'_k} + \mathbf{c}_{k,i_k}^H \mathbf{n}. \tag{3.3}$$

The signal-to-interference-ratio (SIR) for the $i_k th$ symbol of user k is written as

$$\gamma_{k,i_k} = \frac{P_{k,i_k} |\mathbf{c}_{k,i_k}^H \mathbf{a}_{k,i_k}|^2}{\sum_{(k',i'_k)\neq(k,i_k)} P_{k',i'_k} |\mathbf{c}_{k,i_k}^H \mathbf{a}_{k',i'_k}|^2 + (\mathbf{c}_{k,i_k}^H \mathbf{c}_{k,i_k})\sigma^2}, \tag{3.4}$$

where $P_{k,i_k} = A_{k,i_k}^2$ is the received power for the $i_k th$ symbol of user k and σ^2 is the noise spectral density. In conventional multirate matched-filter receiver [53] the receiver filter is chosen the same as the effective spreading signature, $\mathbf{c}_{k,i_k} = \mathbf{a}_{k,i_k}$. In the multirate multiuser receiver the filter coefficients $\mathbf{c}_{k,i_k}$ is selected to maximized the SIR of each symbol. Using the method similar to that in [47] it is derived that

$$\mathbf{c}_{k,i_k} = \frac{\mathbf{Z}_{k,i_k}^{-1} \mathbf{a}_{k,i_k}}{\mathbf{a}_{k,i_k}^H \mathbf{Z}_{k,i_k}^{-1} \mathbf{a}_{k,i_k}}, \tag{3.5}$$

where $\mathbf{Z}_{k,i_k}$ is the covariance matrix of the interference to the $i_k th$ symbol of user k defined as

$$\mathbf{Z}_{k,i_k} \equiv \sum_{(k',i'_k)\neq(k,i_k)} P_{k',i'_k} \mathbf{a}_{k',i'_k} \mathbf{a}_{k',i'_k}^H + \sigma^2 \mathbf{I}. \tag{3.6}$$

The SIR for the $i_k th$ symbol of user k at the multirate multiuser receiver is given by

$$\gamma_{k,i_k} = P_{k,i_k} (\mathbf{a}_{k,i_k}^H \mathbf{Z}_{k,i_k}^{-1} \mathbf{a}_{k,i_k}). \tag{3.7}$$

The adaptive power control algorithm adjusts the transmit powers so that the SIR at the receiver exceeds or equal to the required SIR for all the symbols,

$$\gamma_{k,i_k} \geq \gamma_{k,i_k}^*, \tag{3.8}$$

where γ_{k,i_k}^* is the required SIR for the $i_k th$ symbol of user k.

3.2 Theoretical Bound on Capacity

The question of system capacity can be stated as: for a set of users with M_k-fold data rate and required SIR γ_k^*, $k = 1, \cdots, K$, how to characterize the number of users whose SIR requirements can be simultaneously met via appropriate power control? We derived the following result: The SIR requirements of all the users can be met only if

$$\sum_{k=1}^{K} M_k \cdot \frac{\gamma_k^*}{1+\gamma_k^*} < N, \tag{3.9}$$

where N is the spreading factor for the basic rate.

Proof: Replacing (k, i_k) with $n \equiv \sum_{k'=1}^{k-1} M_{k'} + i_k$, we can index all the symbols as $n = 1, \cdots, \tilde{K}$. Define a covariance matrix of all the symbols as

$$\mathbf{Z} \equiv \sum_{n'=1}^{\tilde{K}} P_{n'} \mathbf{a}_{n'} \mathbf{a}_{n'}^H + \sigma^2 \mathbf{I}. \tag{3.10}$$

The covariance matrix of the interference to the nth symbol defined in (3.6) is written as

$$\mathbf{Z}_n = \mathbf{Z} - P_n \mathbf{a}_n \mathbf{a}_n^H. \tag{3.11}$$

Substitute (3.11) into (3.7)

$$\begin{aligned} \gamma_n &= P_n \mathbf{a}_n^H \mathbf{Z}_n^{-1} \mathbf{a}_n \\ &= P_n \mathbf{a}_n^H (\mathbf{Z} - P_n \mathbf{a}_n \mathbf{a}_n^H)^{-1} \mathbf{a}_n \\ &= P_n \mathbf{a}_n^H (\mathbf{Z}^{-1} + \frac{P_n \mathbf{Z}^{-1} \mathbf{a}_n \mathbf{a}_n^H \mathbf{Z}^{-1}}{1 - P_n \mathbf{a}_n^H \mathbf{Z}^{-1} \mathbf{a}_n}) \mathbf{a}_n \\ &= \frac{\mathbf{a}_n^H \mathbf{Z}^{-1} \mathbf{a}_n P_n}{1 - \mathbf{a}_n^H \mathbf{Z}^{-1} \mathbf{a}_n P_n}. \end{aligned} \tag{3.12}$$

Equation (3.12) can be rewritten as

$$\frac{\gamma_n}{1+\gamma_n} = P_n \mathbf{a}_n^H \mathbf{Z}^{-1} \mathbf{a}_n. \tag{3.13}$$

Summing (3.13) over $n = 1, \cdots, \tilde{K}$ we obtain

$$\begin{aligned}
\sum_{n=1}^{\tilde{K}} \frac{\gamma_n}{1+\gamma_n} &= \sum_{n=1}^{\tilde{K}} \mathbf{a}_n^H \mathbf{Z}^{-1} \mathbf{a}_n P_n \\
&= tr(\mathbf{A}^H \mathbf{Z}^{-1} \mathbf{A} \mathbf{D}) \\
&= tr(\mathbf{A} \mathbf{D} \mathbf{A}^H \mathbf{Z}^{-1}) \\
&= tr(\mathbf{\Lambda}(\mathbf{\Lambda} + \sigma^2 \mathbf{I})^{-1}) \\
&= \sum_{i=1}^{N} \frac{\lambda_i}{\lambda_i + \sigma^2} \\
&< N, \qquad (3.14)
\end{aligned}$$

where $\mathbf{A} \equiv [\mathbf{a}_1, \cdots, \mathbf{a}_{\tilde{K}}]$ is a matrix of effective spreading signatures of all the symbols, $\mathbf{D} \equiv diag(P_1, \cdots, P_{\tilde{K}})$ is a diagonal matrix of received power of all the symbols, $\mathbf{\Lambda} \equiv \mathbf{A}\mathbf{D}\mathbf{A}^H$ is a matrix of dimension $N \times N$, $\mathbf{Z} = \mathbf{\Lambda} + \sigma^2 \mathbf{I}$, and $\lambda_i, i = 1, \cdots, N$ are the eigenvalues of $\mathbf{\Lambda}$. Recall (3.8) we have

$$\sum_{n=1}^{\tilde{K}} \frac{\gamma_n^*}{1+\gamma_n^*} < N. \qquad (3.15)$$

Replace n by (k, i_k) (3.15) can be rewritten as

$$\sum_{k=1}^{K} \sum_{i_k=1}^{M_k} \frac{\gamma_{k,i_k}^*}{1+\gamma_{k,i_k}^*} < N. \qquad (3.16)$$

Assume the required SIR for all M_k symbols of user k are the same, i.e. $\gamma_{k,i_k}^* = \gamma_k^*$, we can rewrite (3.16) as (3.9). $\Box$

The result in (3.9) can be interpreted using the notion of “effective bandwidth”. In a multirate system the effective bandwidth of user k is defined as

$$EB_k \equiv M_k \cdot \frac{\gamma_k^*}{1+\gamma_k^*}. \qquad (3.17)$$

The users’ SIR requirements can be met only if the sum of the effective bandwidths for all the users is less than the degree of freedom, which is the spreading factor for the basic rate in a multirate system. Inequality (3.9) provides a theoretical bound on the capacity of multirate CDMA system with multiuser receiver.

For multirate CDMA system using conventional matched-filter receiver capacity is characterized by

$$\sum_{k=1}^{K} M_k \cdot \gamma_k^* < N. \tag{3.18}$$

proof: For random spreading sequences the SIR of user k can be written as [53]

$$\gamma_k \simeq \frac{P_k}{\sum_{k'=1}^{K} P_{k'} \frac{1}{N} M_{k'} + \sigma^2}. \tag{3.19}$$

Solving the linear equations we have

$$P_k = \frac{\gamma_k \cdot \sigma^2}{1 - \frac{1}{N} \sum_{k'=1}^{K} M_{k'} \gamma_{k'}}. \tag{3.20}$$

Since P_k is positive it is necessary that

$$\sum_{k=1}^{K} M_k \cdot \gamma_k < N. \tag{3.21}$$

Recall (3.8) we obtain (3.18). □

The result in (3.18) can also be interpreted using the notion of "effective bandwidth". In a multirate system with conventional receiver the effective bandwidth of user k is defined as

$$EB_k \equiv M_k \cdot \gamma_k^*. \tag{3.22}$$

The users' SIR requirements can be met only if the sum of the effective bandwidths for all the users is less than the degree of freedom, which is the spreading factor for the basic rate in a multirate system.

3.3 Simulation

In the previous section it is proved that capacity of multirate CDMA system with multiuser receiver can be characterized by a theoretical bound given in (3.9). In this section simulations in multipath fading environment are carried out to study the actual system capacity and compare it with the theoretical bound.

Given a set of users with transmission data rate and required SIR, it is necessary to find out whether the users' SIR requirements can be met simultaneouly or not. If yes, what are the power assignments so that the SIR requirements are met and transmit powers are minimized. To minimize the transmit power, it is required that equality in (3.8) holds, i.e. the SIR at the receiver is equal to the required SIR. The power assignment can be solved by running an iterative power control algorithm:

```
$P'_n = P^i_n$
$\gamma_n = 0$
$while(\gamma_n < \gamma^*_n) and (P'_n \le P^c_n)$
    $P_n = P'_n$
    $\gamma_n = f(P_n)$
    $P'_n = P_n \cdot \frac{\gamma^*_n}{\gamma_n}$
$end$
```

where $n = 1, \cdots, \tilde{K}$, P^i_n and P^c_n are the initial power assignment and power constraint (maximum power allowed) of the nth symbol, respectively, and $f()$ is a function given in (3.7). For a set of users the iterative power control algorithm is run. After the algorithm stops the condition $P'_n \le P^c_n$ is examined. If it holds, i.e. power assignment is less than or equal to the power constrait for all the symbols, then this set of users is said to be feasible. There exists valid power assignment P_n that the SIR requirements of all the symbols can be met. If it does not hold, i.e. power assignment of at least one symbol is larger than the power contraint, then this set of users is not feasible. In the simulation we consider a system with several classes of users. Data rate and required SIR are the same for users in a class. Capacity is expressed as a set of number of users in each class. The set of maximum number of users for which SIR requirements of all the users can be met is said to be the actual system capacity.

3.4 Numerical Results and Discussion

Assume a bandwidth of $W = 4.096$ MHz is allocated for wideband CDMA system. We consider a dual-class system, in which class I users transmit at symbol rate of 64 kbps (basic rate), corresponding to a spreading factor of $N = 64$, and class II users transmit at 128 kbps (two-fold rate), corresponding to a spreading factor of 32. The users' spreading sequences are independently and randomly chosen [47]. Power constraints are expressed in terms of signal-to-noise ratio (SNR) per symbol at the receiver. Multipath is modeled as L paths, each delayed at $l = 0, \cdots, L-1$ chips, and the coefficient $\alpha_{k,i_k,l}$ a complex random variable with $|\alpha_{k,i_k,l}| = 1/\sqrt{L}$, i.e. power is divided equally among the L paths. The required SIR for users in class I and II are denoted as γ_1^* and γ_2^*, respectively.

We first consider a case in which both low rate and high rate users have the same SIR requirement, $\gamma_1^* = 3$ dB and $\gamma_2^* = 3$ dB. The simulation results are depicted in Figure 3.1. For comparison theoretical bound given by (3.9) is also plotted. The actual system capacity in multipath fading environment is always upper bounded by the theoretical bound. At large power constraint (SNR = 30 dB) the actual system capacity for $L = 1$, $L = 2$ and $L = 3$ are almost the same. They are all quite close to the theoretical bound. At lower power contraint (SNR = 10 dB) capacity is reduced by about 1/3. Capacity of multipath channel ($L = 2$ and $L = 3$) is less than that of single path channel ($L = 1$), due to interference caused by the nonzero cross-correlation between the multiple path components of the same user. These results suggest that given relatively large power constraint, multipath diversity can

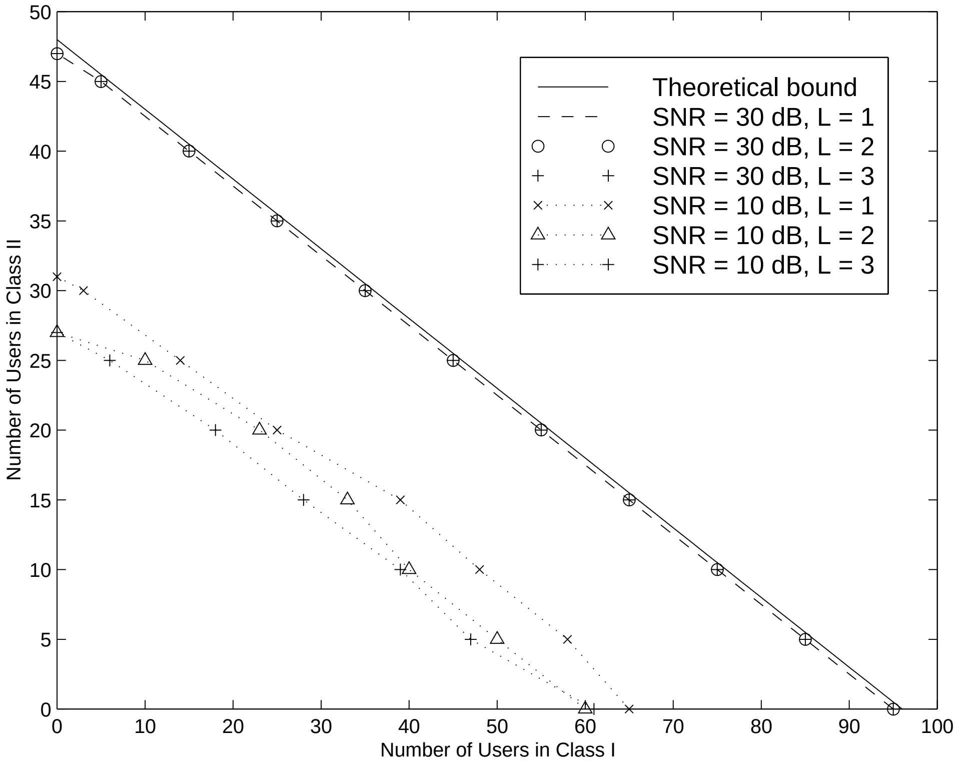

Figure 3.1 Capacity of multirate CDMA system with multiuser receiver. $\gamma_1^* = 3$ dB, $\gamma_2^* = 3$ dB.

be fully exploited such that actual system capacity approaches the theoretical bound. Therefore theoretical bound in (3.9) is quite useful for characterizing capacity of multirate CDMA system.

We now study another case in which high rate users have higher SIR requirement, $\gamma_1^* = 3$ dB and $\gamma_2^* = 6$ dB. The actual system capacity for $L = 3$ and the theoretical bound are plotted in Figure 3.2. At large power constraint (SNR = 30 dB) the actual system capacity is quite close to the theoretical bound. At lower power constraint (SNR = 10 dB) capacity is reduced. The reduction when all users are in class I is about 1/3, while the reduction when all users are in class II is about 3/4. This is due to the higher SIR requirement (6 dB) for class II users and the lower power constraint

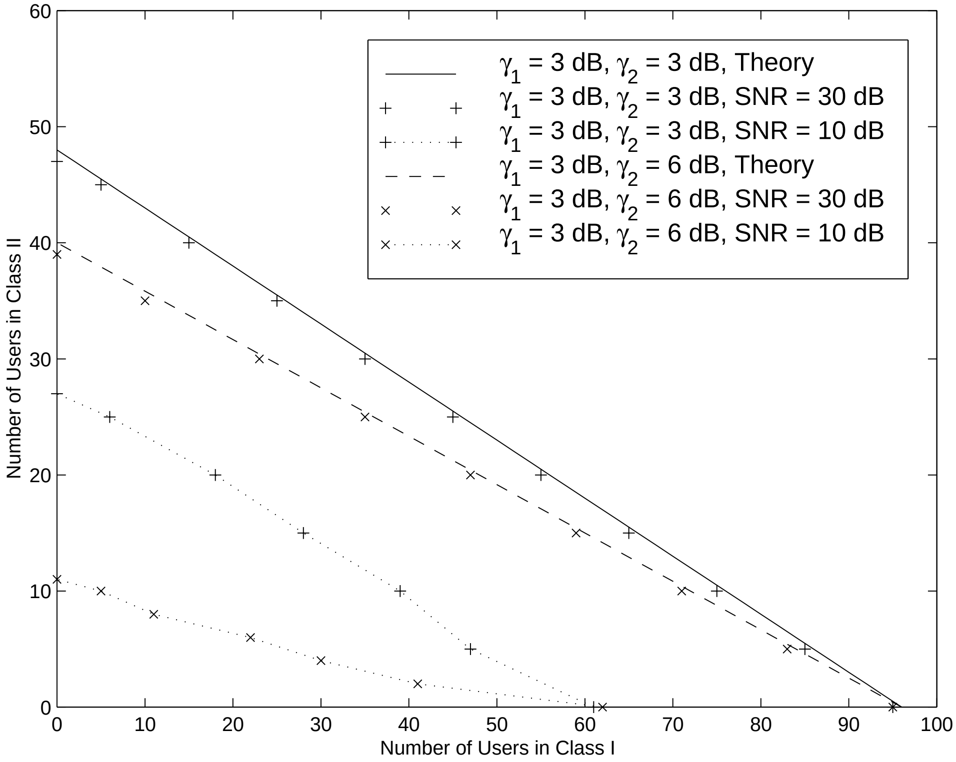

Figure 3.2 Capacity of multirate CDMA system with multiuser receiver.

(SNR = 10 dB). We can compare capacity in this case to that in the previous case ($\gamma_1^* = 3$ dB and $\gamma_2^* = 3$ dB, also plotted). When all the users are in class I capacity is the same, due to the same SIR requirement for class I users in both cases. At large power constraint (SNR = 30 dB) capacity when all users are in class II is about 5/6 that of the previous case, though the SIR requirement for class II users is twice that in the previous case. At lower power constraint (SNR = 10 dB) capacity when all users are in class II is less than 1/2 of that in the previous case. These results show that given large power constraint the multiuser receiver can support users with higher SIR requirement and achieve high capacity in multirate CDMA system.

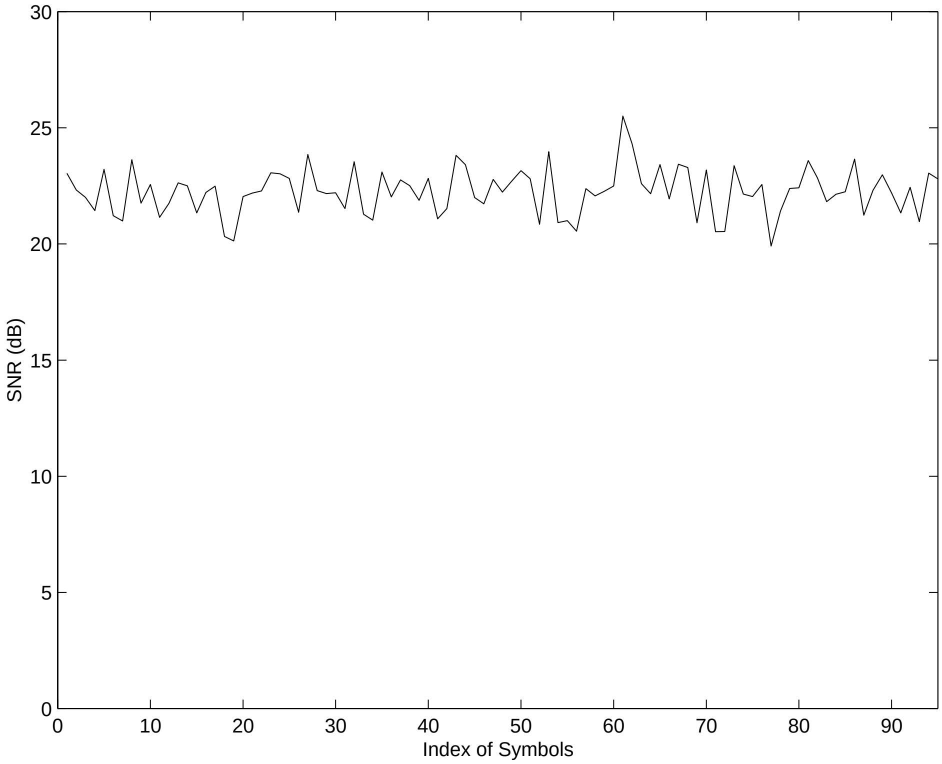

Figure 3.3 Power assignment of all the symbols. $(K_1, K_2) = (45, 25)$.

We now study the effect of adaptive power control on capacity. The following results are for $\gamma_1^* = 3$ dB, $\gamma_2^* = 3$ dB, $L = 3$ and power constraint of $SNR = 30$ dB. Consider an example $(K_1, K_2) = (45, 25)$ which is quite close to the theoretical bound on capacity. The power assignment of all the symbols solved by the iterative power control algorithm is depicted in Figure 3.3. The average SNR of all the symbols is about 22 dB, and the range of SNRs is about 5 dB. The variance of SNR among the symbols is due to the different fading condition in channel and different cross-correlation of random codes. In fixed power control the received SNR is kept the same for all the symbols, clearly this would cause a large variance in SIR among the symbols. This degrades quality of service and/or reduces system capacity. In

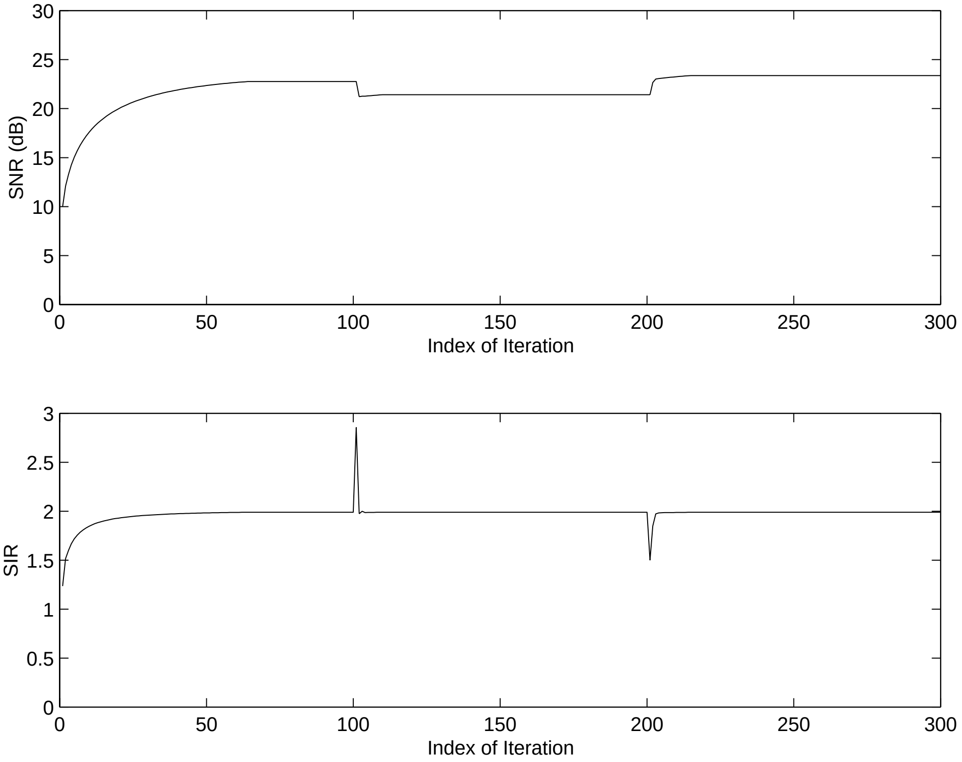

Figure 3.4 Power assignment and SIR for user 1 during iteration. $\tau_c = 100 \cdot t_{PC}$.

contrast to fixed power control, adaptive power control dynamically adjust the SNR according to the fading condition in the channel and cross-correlation of codes such that SIR at the receiver is equal to the required SIR. Figure 3.4 depicts dynamics of adaptive power control. The power assignment and SIR of symbol 1 during iteration are plotted, where τ_c is the time period in which the channel is static, and t_{PC} is the time period between power updates. Assume channel variation caused by fading is slow that $\tau_c = 100 \cdot t_{PC}$. In the first channel state all the symbols start power iteration from initial power assignment of $SNR = 10$ dB, in this case it takes 64 iterations for the SIR to reach the target level. After that power assignment is adjusted according to the change of fading condition in the channel. It only takes a few iterations for the

SIR to converge to the target. This demonstrates that adaptive power control is able to maintain the SIR at the target level in multipath fading channel. The simulation also shows that SIR convergence is faster when system load is lighter, as depicted in Figure 3.5. Bandwidth utility is defined as

$$\eta = \frac{1}{N}\sum_{k=1}^{K} M_k \cdot \frac{\gamma_k^*}{1+\gamma_k^*}, \tag{3.23}$$

which indicates the load in multirate CDMA system. When the load is light ($\eta < 0.85$) it takes less than 10 iterations for SIR to reach the target level, start from initial power assignment of $SNR = 10$ dB. When the load becomes heavier ($\eta > 0.85$) it takes more iterations for SIR to reach the target level. Notice that this is for power iteration in the initial channel state, in the following states it only takes a few iterations for SIR to converge to the target even if η is quite close to 1, as shown in Figure 3.4. The relation of power level and bandwidth utility is depicted in Figure 3.6. When the load is light ($\eta < 0.8$) the average power level is low ($SNR < 10$ dB). The power level increases when the load becomes heavier. The average SNR is larger than 20 dB when η is quite close to 1. The plot shows that a relatively low power level is sufficient for the multirate CDMA system to achieve reasonably high bandwidth utility.

We now study actual system capacity for asynchronous transmission. The results are plotted in Figure 3.7 for $\gamma_1^* = 3$ dB, $\gamma_2^* = 3$ dB, $L = 3$ and power constraint of $SNR = 30$ dB. The delay of users are randomly chosen from 0 to $N-1$ chips. Actual system capacity for synchronous transmission is also plotted for comparison. Capacity for asynchronous transmission is less than that for synchronous transmission. When all users are in class I the reduction is about 1/4, while when all users are class II the reduction is only about 1/10. It shows that asynchronous transmission reduces system capacity, but the reduction is smaller for higher rate users.

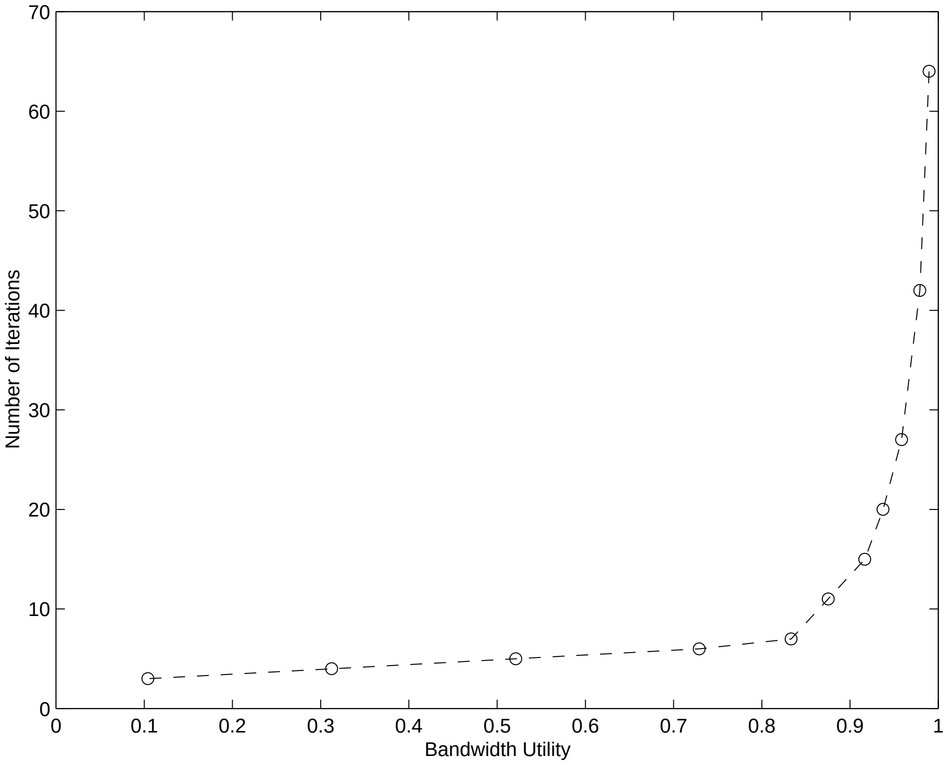

Figure 3.5 Number of iterations vs. bandwidth utility.

We now study capacity of multirate CDMA system using conventional receiver. Here we choose low rate of 32 kbps and high rate of 64 kbps, corresponding to spreading factor of 128 and 64 respectively. The results are plotted in Figure 3.8 for $\gamma_1^* = 3$ dB. Capacity of multipath channel ($L = 2$ and $L = 3$) is less than that of single path channel ($L = 1$), due to interference caused by the nonzero cross-correlation between the multiple path components of the same user. For comparison theoretical result given by (3.18) is also plotted. At large power constraint (SNR = 30 dB) actual system capacity for $L = 1$, $L = 2$ and $L = 3$ are close to the theoretical result. At lower power contraint (SNR = 10 dB) capacity is reduced by about 1/3.

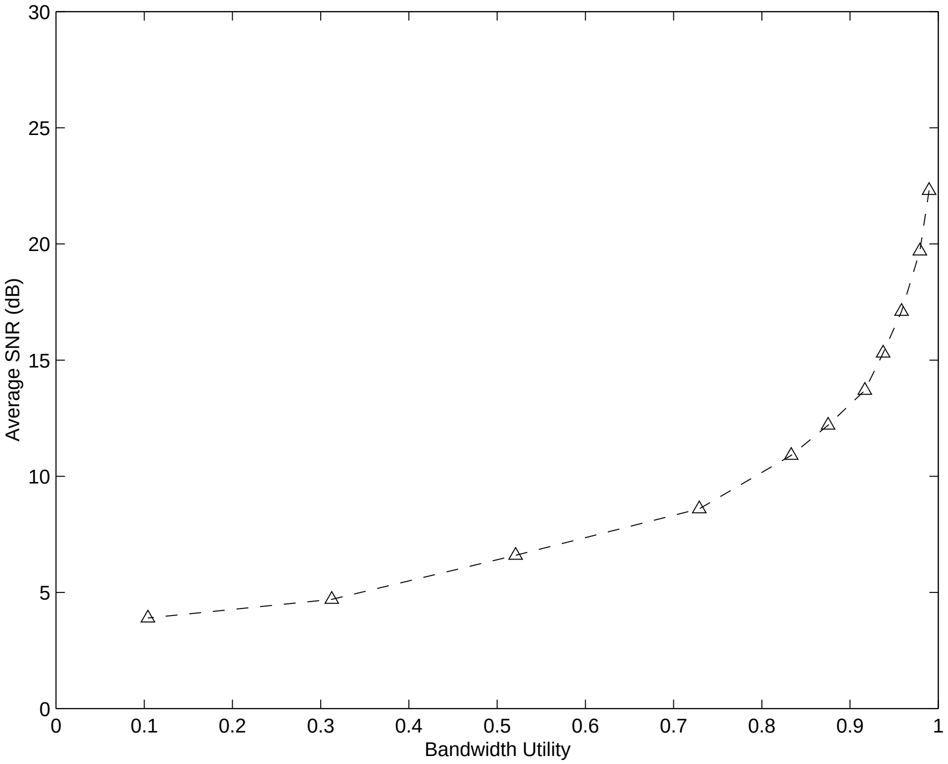

Figure 3.6 Average power vs. bandwidth utility.

These results suggest that for relatively large power constraint system capacity can be characterized by the theoretical result in (3.18).

It is shown in (3.17) that effective bandwidth is a function of symbol rate and required SIR of a user. We can further establish a relation of effective bandwidth and bit error probability. For a user with symbol rate R, the source date rate is $R_s = R \cdot r$, where r is the error correction code rate. In such system total bandwidth expansion is a combination of coding and spreading, and the processing gain $P = 1/r \times N$ where N is the spreading factor. Using rate-compatible punctured convolutional (RCPC) codes [53] the code rate r can be varied. The available source data rate in multirate wideband CDMA system is depicted in Figure 3.9. The code rate can be selected from

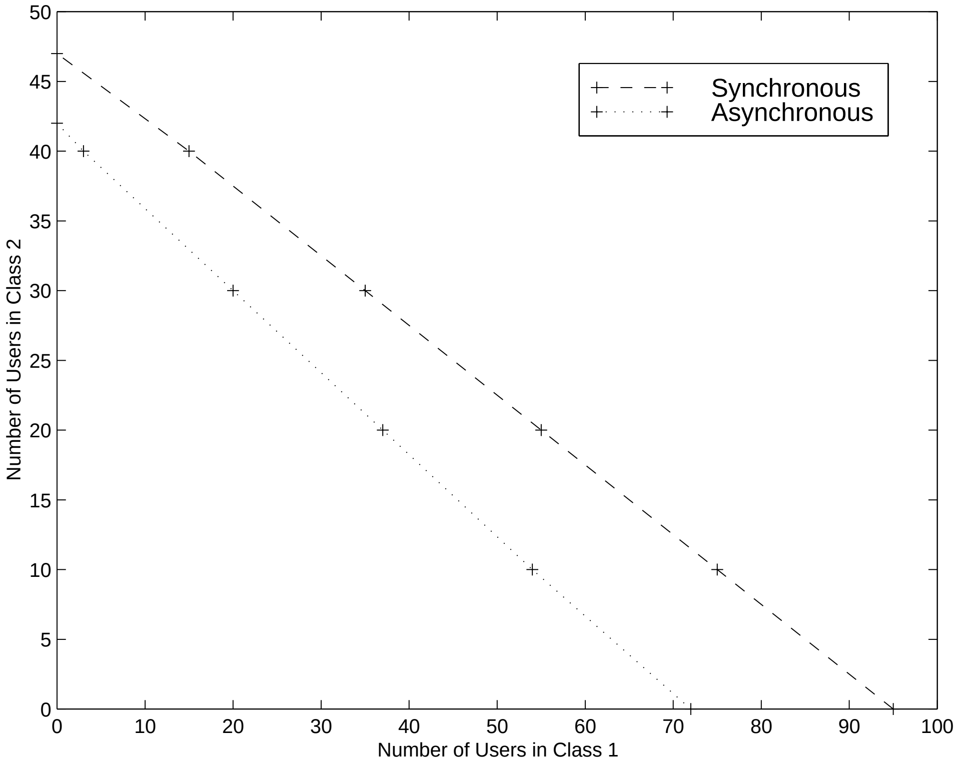

Figure 3.7 Capacity of synchronous and asynchronous multirate CDMA system with multiuser receiver.

$r = 0.1$ to $r = 1$ ($r = 1$ denotes no error correction coding). The spreading factor can vary from 2 to 512, corresponding to symbol rates from 8 kbps to 2.048 Mbps. For each code rate the required SIR to achieve the target bit error probability can be calculated based on the performance bound of the RCPC codes as given in [53]. The effective bandwidth of a user with given source date rate and bit error probability is then calculated. The results are depicted in Figure 3.10 for BER = 10^{-3} and BER = 10^{-6} respectively. The plots demonstrate clearly to support a user with certain source data rate and required bit error probability, how much bandwidth needs to be allocated to the user. This provides an abstraction of bandwidth resource at the network layer and facilitates the task of admission control in multirate CDMA

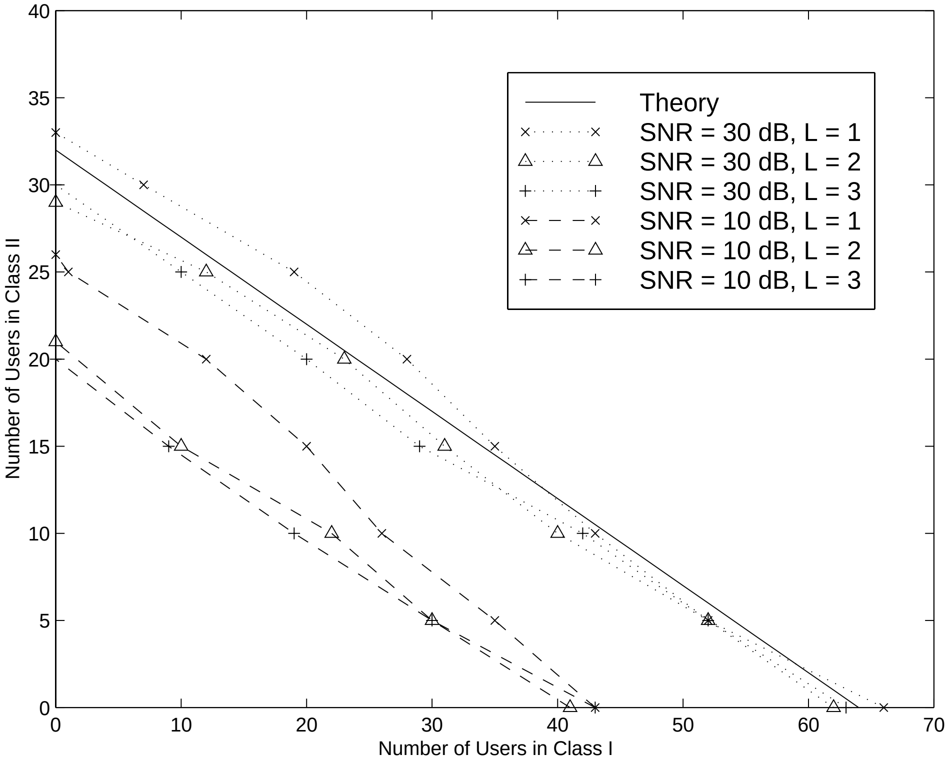

Figure 3.8 Capacity of multirate CDMA system with conventional receiver. $N_1 = 128$, $N_2 = 64$.

system with multiuser receiver. It shows that given code rate and BER requirement, the effective bandwidth is proportional to the source data rate. Given source data rate and code rate, the effective bandwidth is larger for lower required BER. Given source bit rate and required BER, the effective bandwidth is smaller at large code rate. This suggests that large code rate is more favorable in CDMA system with mutliuser receiver, i.e., more of bandwidth expansion should be allocated to spreading.

The effective bandwidth of multirate CDMA system with conventional receiver, as defined in (3.22), is also depicted in Figure 3.10. This provides an abstraction of bandwidth resource in multi-class traffic CDMA system with conventional receiver. In contrast to the multiuser case, for given source bit rate and required BER the

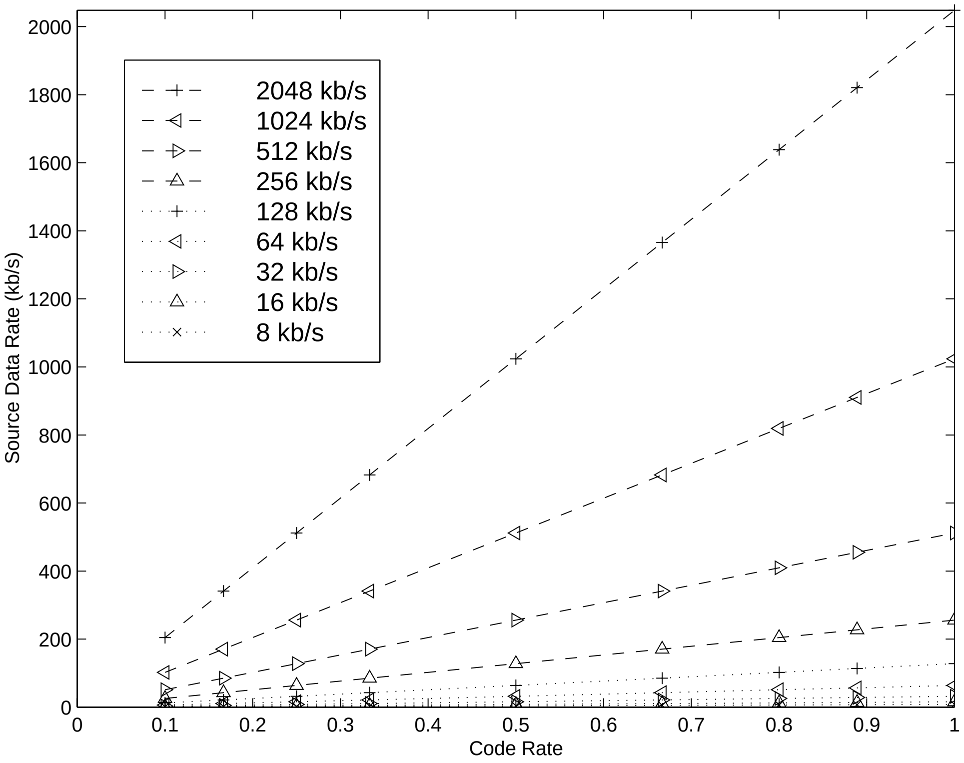

Figure 3.9 Source data rate in multirate wideband CDMA system.

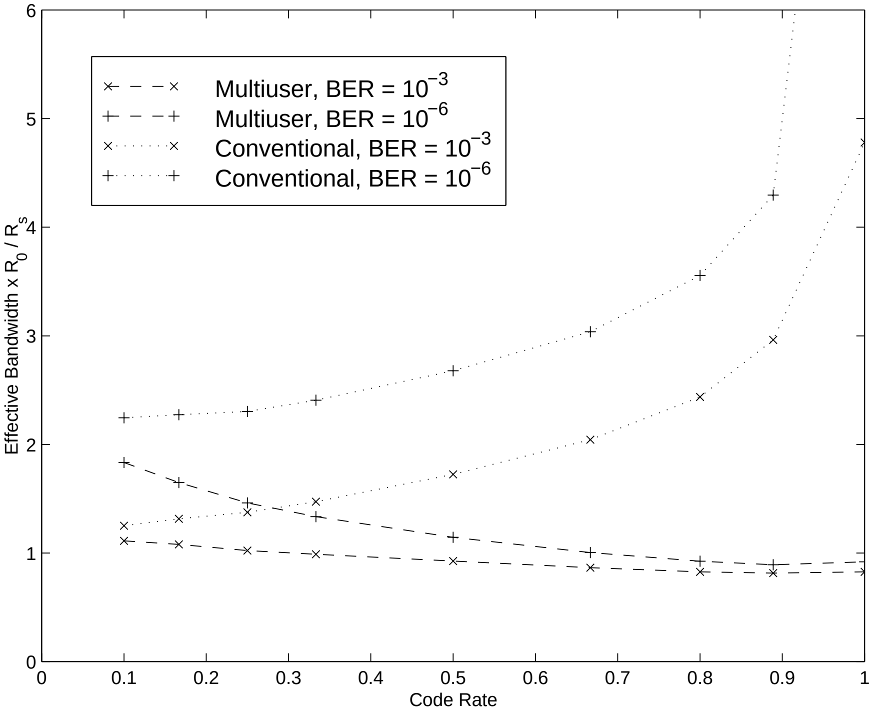

Figure 3.10 Effective bandwidth vs. code rate in multi-class CDMA system. R_s: source data rate, R_0: basic symbol rate.

effective bandwidth is smaller at small code rate. This suggests that small code rate is more favorable in CDMA system with conventional receiver, i.e., more of bandwidth expansion should be allocated to coding. These are similar to the results in [103].

We can compare capacity of CDMA system with multiuser receiver and conventional receiver by looking at the ratio of the effective bandwidths of conventional receiver and multiuser receiver, EB_{conv}/EB_{mu}, as plotted in Figure 3.11. It shows that EB_{conv}/EB_{mu} increases as code rate increases. Notice that for higher source bit rate the available bandwidth expansion is small, and only large code rate can be used, as shown in Figure 3.9. Therefore multiuser receiver is quite effective in increasing capacity of users with *higher* data rate. It is also shown that EB_{conv}/EB_{mu} for BER of 10^{-6} is larger than that for BER of 10^{-3}. Therefore multiuser receiver is quite effective in increasing capacity of users with *lower* target bit error probability. Notice that these results are valid in multipath fading environment at large power contraint.

3.5 Summary

In this chapter we developed a new resource allocation scheme using adaptive power control and multirate multiuser receiver. The scheme can support multiple classes of traffic with different data rates and bit error rate and guarantee their quality of service requirements in multipath fading environment. Our approach is that both transmit power and receiver filter adapt to the time-varying fading channel state. A multirate multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each symbol is proposed for multirate CDMA system. It is combined with adaptive power control based on required SIR to provide different quality of service for multiple-data-rate traffic. A theoretical bound is derived to characterize the capacity of multi-class CDMA system using the multiuser receiver. Simulations show that actual system

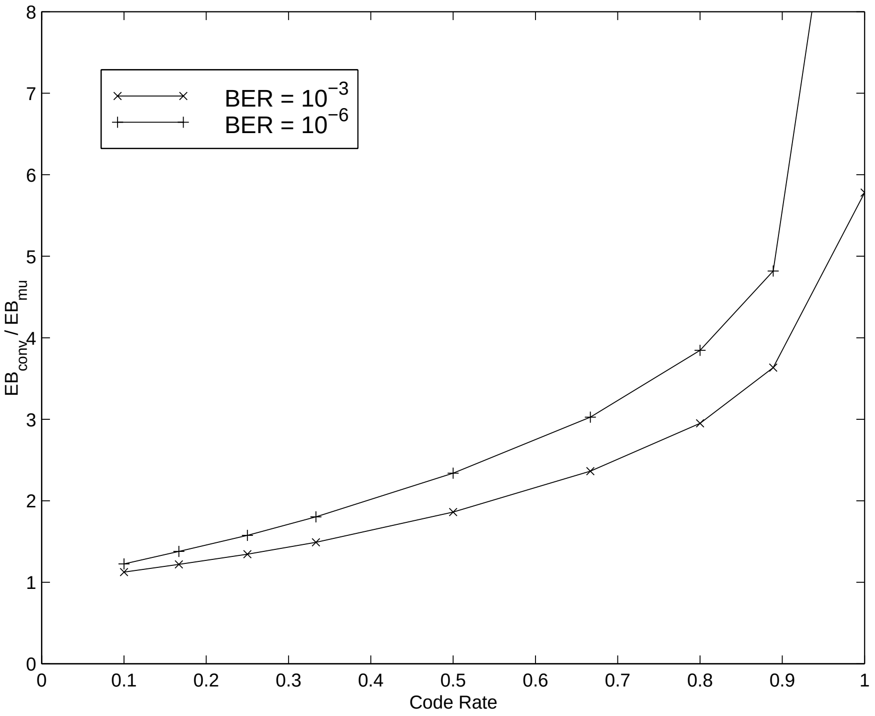

Figure 3.11 Ratio of effective bandwidths of conventional receiver and multiuser receiver.

capacity in multipath fading environment is close to the theoretical bound at large power constraint. It is also demonstrated that the multirate multiuser receiver is quite effective in increasing capacity of users with *higher* source data rate and *lower* target bit error rate.

Chapter 4

CDMA System with Antenna Array Multiuser Receiver

Next generation wireless networks will support a large number of users with different quality of service (QoS) requirement such as data rate and bit error probability. Antenna array or space-time processing can improve performance, coverage and capacity of wireless communication systems. In most of previous works various antenna array receivers are proposed and performance improvement in the physical layer in terms of lower bit error rate are demonstrated. They generally assume either no power control or some simple fixed power control scheme and consider only single class traffic with same data rate and bit error rate. In this chapter we study resource allocation and capacity of CDMA system using antenna array multiuser receiver to support multiple classes of users with different quality of service requirements. We propose a new resource allocation scheme applying joint adaptive power control and antenna array multiuser detection in multipath fading channel. Our approach is that both transmit power and receiver filter adapt to the time-varying fading channel state. An antenna array multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each user is proposed. It is combined with adaptive power control based on required SIR to support users with different bit error probability (BER) requirements. A theoretical bound is derived to characterize capacity of CDMA system using the antenna array multiuser receiver. Simulations are carried out to study the actual system capacity in a multipath fading environment. The rest of the chapter is organized as follows:

Section 4.1 describes the CDMA system model. In Section 4.2 a theoretical bound is derived for characterizing capacity of CDMA system using antenna array multiuser receiver. Section 4.3 simulations in multipath fading environment are described. In Section 4.4 numerical results and discussion are presented. Main results are summarized in Section 4.5. This chapter focuses on single cell CDMA system using antenna array multiuser receiver. Cellular CDMA system are discussed in Chapter 5.

4.1 System Description

We consider a direct-sequence CDMA system with BPSK modulation and coherent detection, and focus on synchronous transmission in the uplink. The received signal at the antenna array receiver is a superposition of multiple copies of attenuated and delayed signals transmitted by all the K users. The signal at the mth antenna is given by

$$r^{(m)}(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} A_k \alpha_{k,l} \rho_{k,l}^{(m)} b_k s_k(t - iT - \tau_{k,l}) + n^{(m)}(t), \tag{4.1}$$

where L_k is the number of paths associated with user k, A_k , b_k and $s_k(t)$ are the received amplitude, the transmitted bit, and the spreading waveform for user k respectively, $\tau_{k,l}$ and $\alpha_{k,l}$ are the delay and the complex coefficient associated with path l for user k respectively, $\rho_{k,l}^{(m)}$ is the array response factor at the mth antenna associated with path l for user k, and $n(t)$ is the additive white gaussian noise (AWGN). The received vector sampled at chip rate in a symbol period can be written as

$$\mathbf{r}_i^{(m)} = \sum_{k=1}^{K} (A_k [\sum_{l=1}^{L_k} \alpha_{k,l} \rho_{k,l}^{(m)} \mathbf{s}_k^{+}(l)] b_{i,k} + A_k [\sum_{l=1}^{L_k} \alpha_{k,l} \rho_{k,l}^{(m)} \mathbf{s}_k^{-}(l)] b_{i-1,k}) + \mathbf{n}_i^{(m)}, \tag{4.2}$$

where $\mathbf{s}_k^{+}(l)$ and $\mathbf{s}_k^{-}(l)$ contain the chip matched-filter output samples of $s_k(t - \tau_{k,l})$ and $s_k(t + T - \tau_{k,l})$, respectively. Notice that $\mathbf{s}_k^{+}(l)$ and $\mathbf{s}_k^{-}(l)$ are vectors of dimension

$N \times 1$, where N is the spreading factor. We can rewrite (4.2) as

$$\mathbf{r}_i^{(m)} = \sum_{k=1}^{K} (A_k \mathbf{a}_k^{+(m)} b_{i,k} + A_k \mathbf{a}_k^{-(m)} b_{i-1,k}) + \mathbf{n}_i^{(m)}, \tag{4.3}$$

where

$$\mathbf{a}_k^{\pm(m)} \equiv \sum_{l=1}^{L_k} \alpha_{k,l} \rho_{k,l}^{(m)} \mathbf{s}_k^{\pm}(l). \tag{4.4}$$

In the case of synchronous transmission, the ith bits of all the users are aligned. Also for DS-CDMA applications, it is typically assumed that the path delays $\tau_{k,l}$ span at most a few chips, the intersymbol interference (ISI) due to multipath vectors $\mathbf{a}_k^-$ (i.e. $i-1th$ bit) is then quite small and is therefore ignored [29]. The received signal vector can be written as

$$\mathbf{r}^{(m)} = \sum_{k=1}^{K} A_k b_k \mathbf{a}_k^{(m)} + \mathbf{n}^{(m)}. \tag{4.5}$$

The subscripts i and superscripts $+$ are dropped since the detection window overlaps with the ith bit and ISI from the $i-1th$ bit is ignored. The received signal vectors of M antennas are processed jointly in the antenna array multiuser receiver. Concatenating signal vectors $\mathbf{r}^{(m)}, m = 1, \cdots, M$ we can define a joint signal vector $\mathbf{r} \equiv [(\mathbf{r}^{(1)})^H, \cdots, (\mathbf{r}^{(M)})^H]^H$. According to (4.5)

$$\mathbf{r} = \sum_{k=1}^{K} A_k b_k \mathbf{a}_k + \mathbf{n}, \tag{4.6}$$

where $\mathbf{a}_k \equiv [(\mathbf{a}_k^{(1)})^H, \cdots, (\mathbf{a}_k^{(M)})^H]^H$ is an $MN \times 1$ vector. One can think $\mathbf{a}_k$ as the "effective spatial-spreading signature" of user k which is the sum of spatial-spreading signatures of the L_k paths of user k. In the receiver a spatial-spreading filter with coefficients $\mathbf{c}_k$ is used to demodulate user k and the receiver statistic is given by

$$\mathbf{c}_k^H \mathbf{r} = A_k \mathbf{c}_k^H \mathbf{a}_k b_k + \sum_{k' \neq k} A_{k'} \mathbf{c}_k^H \mathbf{a}_{k'} b_{k'} + \mathbf{c}_k^H \mathbf{n}. \tag{4.7}$$

The signal-to-interference-ratio (SIR) for user k can be written as

$$\gamma_k = \frac{P_k |\mathbf{c}_k^H \mathbf{a}_k|^2}{\sum_{k' \neq k} P_{k'} |\mathbf{c}_k^H \mathbf{a}_{k'}|^2 + (\mathbf{c}_k^H \mathbf{c}_k)\sigma^2}, \tag{4.8}$$

where $P_k = A_k^2$ is the received power for user k and σ^2 is the noise spectral density. In conventional antenna array matched-filter receiver the spatial-spreading filter is chosen to be the same as the effective spatial-spreading signature for user k, $\mathbf{c}_k = \mathbf{a}_k$. In the antenna array multiuser receiver the filter coefficients $\mathbf{c}_k$ is selected to maximized the SIR of each user. Using the method similar to that in [47] it is derived that

$$\mathbf{c}_k = \frac{\mathbf{Z}_k^{-1}\mathbf{a}_k}{\mathbf{a}_k^H \mathbf{Z}_k^{-1}\mathbf{a}_k}, \tag{4.9}$$

where $\mathbf{Z}_k$ is the covariance matrix of the interference to user k defined as

$$\mathbf{Z}_k \equiv \sum_{k' \neq k} P_{k'} \mathbf{a}_{k'} \mathbf{a}_{k'}^H + \sigma^2 \mathbf{I}. \tag{4.10}$$

The SIR for user k at the antenna array multiuser receiver is given by

$$\gamma_k = P_k(\mathbf{a}_k^H \mathbf{Z}_k^{-1} \mathbf{a}_k). \tag{4.11}$$

The adaptive power control algorithm adjusts the transmit powers so that the SIR at the receiver exceeds or equal to the required SIR for all the users,

$$\gamma_k \geq \gamma_k^*, \tag{4.12}$$

where γ_k^* is the required SIR for user k.

4.2 Theoretical Bound on Capacity

The question of system capacity can be stated as: for a set of users with required SIR $\gamma_k^*, k = 1, \cdots, K$, how to characterize the number of users whose SIR requirements can be simultaneously met via appropriate power control? We derived the following result: The SIR requirements of all the users can be met only if

$$\sum_{k=1}^{K} \frac{\gamma_k^*}{1 + \gamma_k^*} < MN, \tag{4.13}$$

where N is the spreading factor and M is the number of antennas in the antenna array.

Proof: Define a covariance matrix of all the users as

$$\mathbf{Z} \equiv \sum_{k'=1}^{K} P_{k'} \mathbf{a}_{k'} \mathbf{a}_{k'}^{H} + \sigma^2 \mathbf{I}. \tag{4.14}$$

The covariance matrix of the interference to user k defined in (4.10) is written as

$$\mathbf{Z}_k = \mathbf{Z} - P_k \mathbf{a}_k \mathbf{a}_k^H. \tag{4.15}$$

Substitute (4.15) into (4.11)

$$\begin{aligned} \gamma_k &= P_k \mathbf{a}_k^H \mathbf{Z}_k^{-1} \mathbf{a}_k \\ &= P_k \mathbf{a}_k^H (\mathbf{Z} - P_k \mathbf{a}_k \mathbf{a}_k^H)^{-1} \mathbf{a}_k \\ &= P_k \mathbf{a}_k^H (\mathbf{Z}^{-1} + \frac{P_k \mathbf{Z}^{-1} \mathbf{a}_k \mathbf{a}_k^H \mathbf{Z}^{-1}}{1 - P_k \mathbf{a}_k^H \mathbf{Z}^{-1} \mathbf{a}_k}) \mathbf{a}_k \\ &= \frac{\mathbf{a}_k^H \mathbf{Z}^{-1} \mathbf{a}_k P_k}{1 - \mathbf{a}_k^H \mathbf{Z}^{-1} \mathbf{a}_k P_k}. \end{aligned} \tag{4.16}$$

Eqn. (4.16) can be rewritten as

$$\frac{\gamma_k}{1 + \gamma_k} = P_k \mathbf{a}_k^H \mathbf{Z}^{-1} \mathbf{a}_k. \tag{4.17}$$

Summing (4.17) over $k = 1, \cdots, K$

$$\begin{aligned} \sum_{k=1}^{K} \frac{\gamma_k}{1 + \gamma_k} &= \sum_{k=1}^{K} \mathbf{a}_k^H \mathbf{Z}^{-1} \mathbf{a}_k P_k \\ &= tr(\mathbf{A}^H \mathbf{Z}^{-1} \mathbf{A} \mathbf{D}) \\ &= tr(\mathbf{A} \mathbf{D} \mathbf{A}^H \mathbf{Z}^{-1}) \\ &= tr(\mathbf{\Lambda} (\mathbf{\Lambda} + \sigma^2 \mathbf{I})^{-1}) \\ &= \sum_{i=1}^{MN} \frac{\lambda_i}{\lambda_i + \sigma^2} \\ &< MN, \end{aligned} \tag{4.18}$$

where $\mathbf{A} \equiv [\mathbf{a}_1, \cdots, \mathbf{a}_K]$ is an $MN \times K$ matrix of all the effective spatial-spreading signatures, $\mathbf{D} \equiv diag(P_1, \cdots, P_K)$ is an $K \times K$ diagonal matrix of the received powers, $\mathbf{\Lambda} \equiv \mathbf{A}\mathbf{D}\mathbf{A}^H$ is a matrix of dimension $MN \times MN$, $\mathbf{Z} = \mathbf{\Lambda} + \sigma^2\mathbf{I}$, and $\lambda_i, i = 1, \cdots, MN$ are the eigenvalues of matrix $\mathbf{\Lambda}$. Since $\mathbf{\Lambda}$ is an Hermitian matrix, i.e. $\mathbf{\Lambda} = \mathbf{\Lambda}^H$, the eigenvalues λ_i are real and positive. This ensures the inequlity in (4.18) is satisfied.

The result in (4.13) can be interpreted using the notion of "effective bandwidth". The effective bandwidth of user k is defined as

$$EB_k \equiv \frac{\gamma_k^*}{1 + \gamma_k^*}. \tag{4.19}$$

The users' SIR requirements can be met only if the sum of the effective bandwidths for all the users is less than the degree of freedom. The degree of freedom in a CDMA system using antenna array multiuser receiver is the *product* of the number of antennas and the spreading factor. Inequality (4.13) provides a theoretical bound on the capacity of CDMA system with antenna array multiuser receiver.

4.3 Simulation

In the previous section it is proved that capacity of CDMA system with antenna array multiuser receiver can be characterized by a theoretical bound given in (4.13).

Given a set of users with required SIR, it is necessary to find out whether the users' SIR requirements can be met simultaneously or not. If yes, what are the power assignments so that the SIR requirements are met and transmit powers are minimized. To minimize the transmit power, it is required that equality in (4.12) holds, i.e. the SIR at the receiver is equal to the required SIR. The power assignment can be solved by running an iterative power control algorithm:

```
$P'_k = P^i_k$
$\gamma_k = 0$
$while(\gamma_k < \gamma^*_k) and (P'_k \leq P^c_k)$
$P_k = P'_k$
$\gamma_k = f(P_k)$
$P'_k = P_k \cdot \frac{\gamma^*_k}{\gamma_k}$
$end$
```

where $k = 1, \cdots, K$, P^i_k and P^c_k are the initial power assignment and power constraint (maximum power allowed) of user k, respectively, and $f()$ is a function given in (4.11). For a set of users the iterative power control algorithm is run. After the algorithm stops the condition $P'_k \leq P^k_n$ is examined. If it holds, i.e. power assignment is less than or equal to the power constrait for all the users, then this set of users is said to be feasible. There exists valid power assignment P_k that the SIR requirements of all the users can be met. If it does not hold, i.e. power assignment of at least one user is larger than the power contraint, then this set of users is not feasible. In the simulation we consider a system with several classes of users. Required SIR are the same for users in a class. Capacity is expressed as a set of number of users in each class. The maximum set of number of users for which SIR requirements of all the users can be met is said to be the actual system capacity.

4.4 Numerical Results and Discussion

Assume a bandwidth of $W = 4.096$ MHz is allocated for wideband CDMA system. The transmit symbol rate is 64 kbps, corresponding to a spreading factor of $N = 64$. The users' spreading sequences are independently and randomly chosen [47]. There are K users uniformly distributed in a cell, and the antenna array multiuser receiver is located at the base station in the center of the cell. Power constraints are expressed in terms of signal-to-noise ratio (SNR) at the receiver, instead of modeling the constraint on users' transmit power and path loss.

Multipath is modeled as L paths, each delayed at $l = 0, \cdots, L-1$ chips, and the coefficient $\alpha_{k,l}$ a complex random variable with $|\alpha_{k,l}| = 1/\sqrt{L}$, i.e. power is divided equally among the L paths. The angle of arrival (AOA) of these paths are uniformly distributed within $[\theta_k - \theta_d/2, \theta_k + \theta_d/2]$, where θ_k is the AOA of user k and θ_d is the dispersion angle of the multipaths for each user. In the simulation a uniform circular array (UCA) is used in the receiver [63]. The array response factor is given by

$$\rho_{k,l}^{(m)} = exp[j\pi cos(2\pi(m-1)/M - \theta_{k,l})], \tag{4.20}$$

where $\theta_{k,l}$ is the angle of arrival of path l of user k. We consider a dual-class system in which the required SIR for users in class I and II are denoted as γ_1^* and γ_2^*, respectively.

We first study a case in which class I and class II users have the same SIR requirement γ^*. This is actually a single class system and capacity can be expressed as total number of users in the system. The actual system capacity for antenna array multiuser receiver with different number of antennas is depicted in Figure 4.1. The required SIR $\gamma^* = 3$ dB and $\theta_d = 60°$. For comparison theoretical bound given by (4.13) is also plotted. The actual system capacity in multipath fading environment is always upper bounded by the theoretical bound. At large power constraint (SNR = 30 dB) the actual system capacity for $L = 1$ and $L = 3$ are almost the same. They are all quite close to the theoretical bound. At lower power contraint (SNR = 10 dB) capacity is reduced. Notice that the percentage of reduction is much lower with larger number of antennas, e.g. for $L = 3$ the reduction in capacity is about 1/2 for $M = 1$ while the reduction is only about 1/5 for $M = 6$. This shows that using mul-

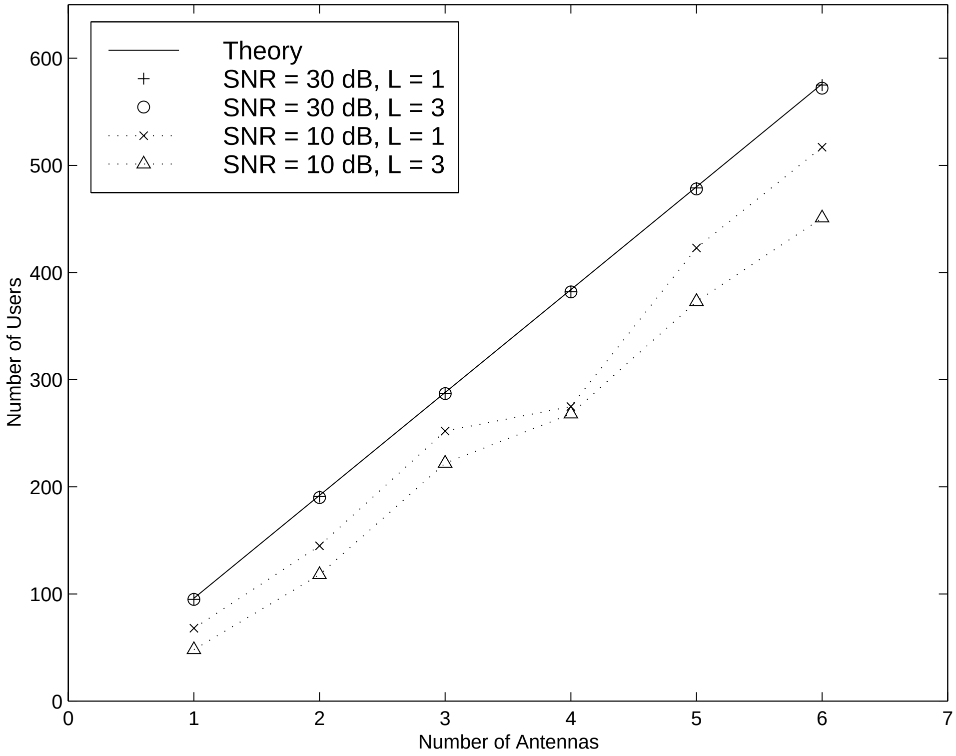

Figure 4.1 Capacity of CDMA system with antenna array multiuser receiver vs. power constraint.

tiple antennas increases the bandwidth utility at lower power constraint. Capacity of multipath channel ($L = 3$) is less than that of single path channel ($L = 1$), due to interference caused by the nonzero cross-correlation between the multiple path components of the same user. These results suggest that given relatively large power constraint, multipath diversity can be fully exploited such that actual system capacity approaches the theoretical bound. Therefore theoretical bound in (4.13) is quite useful for characterizing capacity of CDMA system with antenna array multiuser receiver.

We now study capacity of CDMA system using antenna array multiuser receiver with higher SIR requirement, $\gamma^* = 6$ dB. The actual system capacity for $L = 3$,

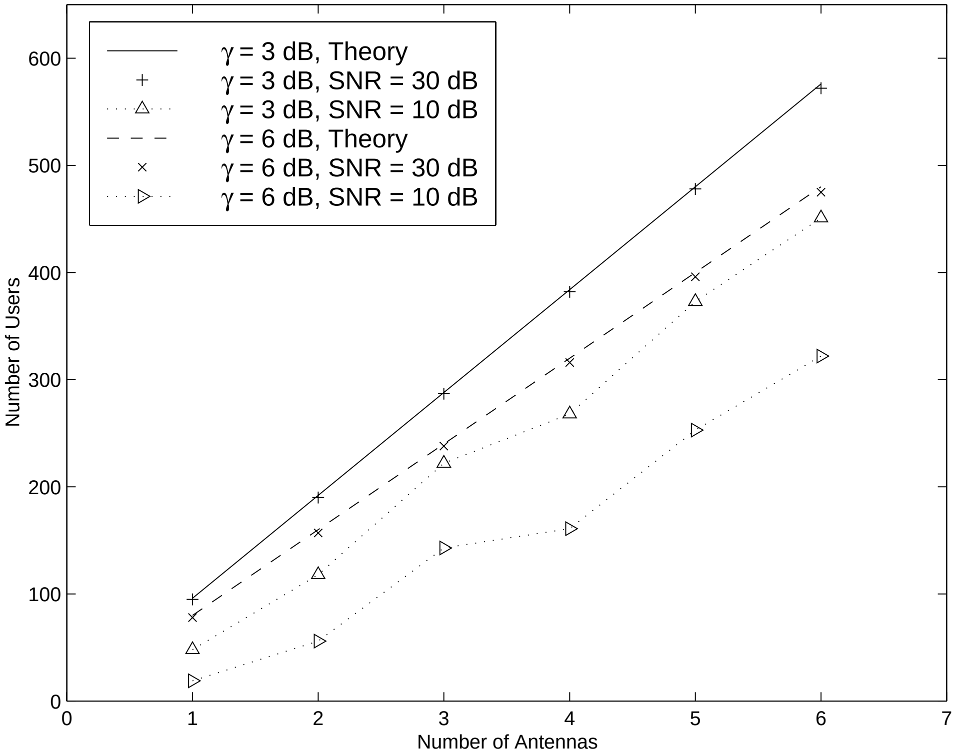

Figure 4.2 Capacity of CDMA system with antenna array multiuser receiver vs. required SIR.

$\theta_d = 60^\circ$ and the theoretical bound are plotted in Figure 4.2. At large power constraint (SNR = 30 dB) the actual system capacity is quite close to the theoretical bound. At lower power constraint (SNR = 10 dB) capacity is reduced. For $M = 1$ the reduction is about 3/4, while for $M = 6$ the reduction is about 1/3. This shows that using multiple antennas increases the bandwidth utility at lower power constraint. Considering that required SIR $\gamma^* = 6$ dB is close to the power constriant SNR = 10 dB, it is significant that system with 6 antennas can still support 320 users.We can compare capacity in this case to that in the previous case ($\gamma^* = 3$ dB, also plotted). While the SIR requirement is twice that of the previous case, capacity is about 5/6 that of the previous case at large power constraint (SNR = 30 dB). Capacity is about

7/10 of that in the previous case for $M = 6$ at lower power constraint (SNR = 10 dB). These results show that the antenna array multiuser receiver can support users with higher SIR requirement and achieve high capacity in CDMA system.

We now compare the capacity of CDMA system using antenna array multiuser receiver and antenna array matched-filter receiver. The actual system capacity for $\gamma^* = 3$ dB, $\theta_d = 60°$ and power constraint SNR = 30 dB as well as the theoretical bound are plotted in Figure 4.3. Capacity of system using antenna array matched-filter receiver is considerably lower than that of antenna array multiuser receiver. For example capacity of matched-filter receiver with 6 antennas is less than that of multiuser receiver with 2 antennas. Therefore using the antenna array multiuser receiver provides significantly high system capacity than antenna array matched-filter receiver.

We now study the effect of adaptive power control on capacity. The following results are for $\gamma_1^* = 3$ dB, $\gamma_2^* = 3$ dB, $M = 3$, $L = 3$, $\theta_d = 60°$ and power constraint of $SNR = 30$ dB. Consider an example $K = 287$ which is quite close to the theoretical bound on capacity. The power assignment of all the users solved by the iterative power control algorithm is depicted in Figure 4.4. The average SNR of all the users is about 25 dB, and the range of SNRs is about 5 dB. The variance of SNR among the users is due to the different fading condition in channel and different cross-correlation of random codes. In fixed power control the received SNR is kept the same for all the users, clearly this would cause a large variance in SIR among the users. This degrades quality of service and/or reduces system capacity. In contrast to fixed power control, adaptive power control dynamically adjust the SNR according to the fading condition in the channel and cross-correlation of codes such that SIR at the receiver is equal to the required SIR. Figure 4.5 depicts dynamics of adaptive power control for $K = 270$. The power assignment and SIR of user 1 during iteration are plotted, where τ_c is the

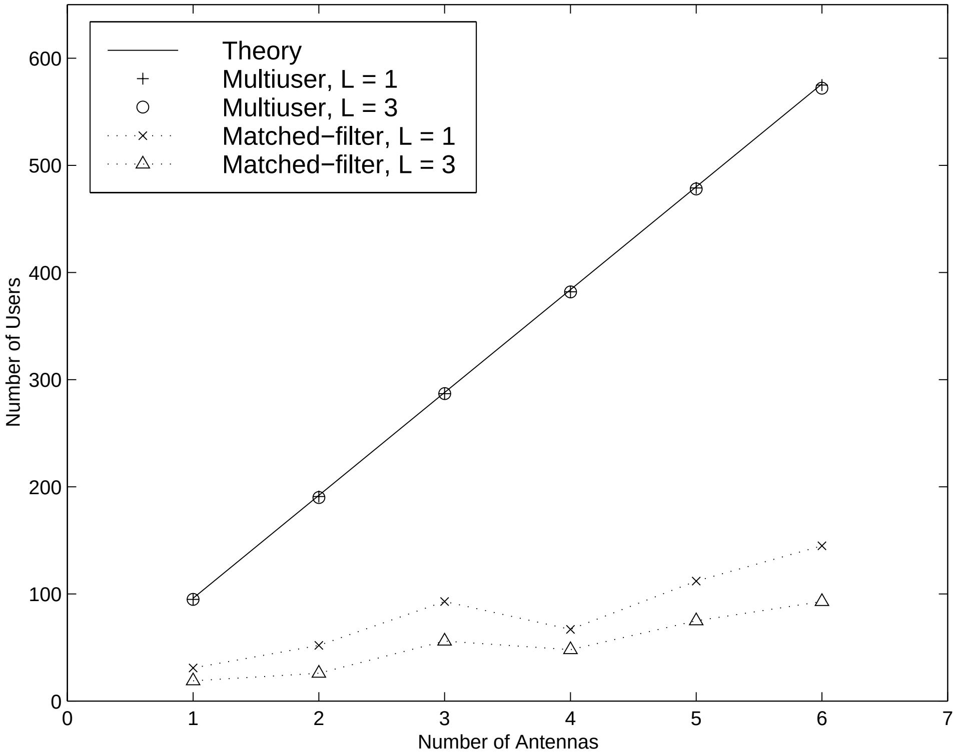

Figure 4.3 Capacity of CDMA system with antenna array multiuser receiver and matched-filter receiver.

time period in which the channel is static, and t_{PC} is the time period between power updates. Assume channel variation caused by fading is slow that $\tau_c = 20 \cdot t_{PC}$. In the first channel state all the users start power iteration from initial power assignment of $SNR = 10$ dB, and SIR converges to the target level during iteration. After that power assignment is adjusted according to the change of fading condition in the channel. It only takes a few iterations for the SIR to converge to the target level. This demonstrates that adaptive power control is able to maintain the SIR at the target level in multipath fading channel. The relation of average power level and bandwidth

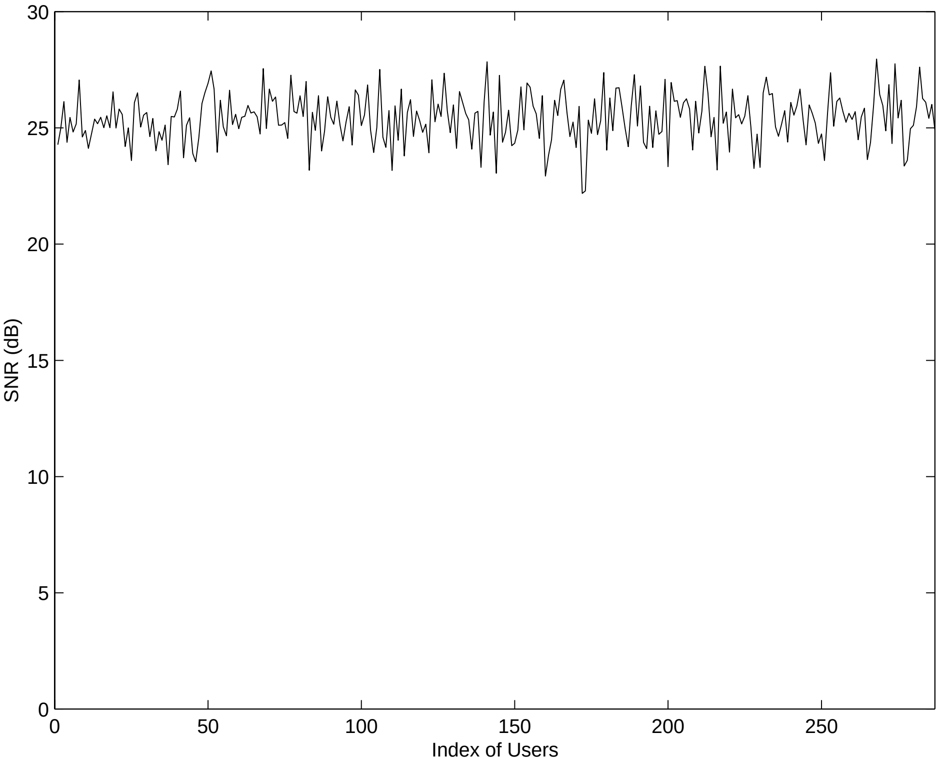

Figure 4.4 Power assignment of all the users. $K = 287$.

utility is depicted in Figure 4.6. Bandwidth utility is defined as

$$\eta \equiv \frac{1}{MN} \sum_{k=1}^{K} \frac{\gamma_k^*}{1+\gamma_k^*}, \tag{4.21}$$

which indicates the load in CDMA system. The average power increases monotonically as the bandwidth utility increases. For antenna array multiuser receiver ($M = 3$) the average power is low ($SNR < 10$ dB) when load is light ($\eta < 0.87$). The average SNR is larger than 20 dB only when η is quite close to 1 ($\eta > 0.98$). The plot shows that a relatively low power level is sufficient for CDMA system with antenna array multiuser receiver to achieve reasonably high bandwidth utility. For the same bandwidth utility, the average SNR is 5 dB lower than of single antenna multiuser receiver

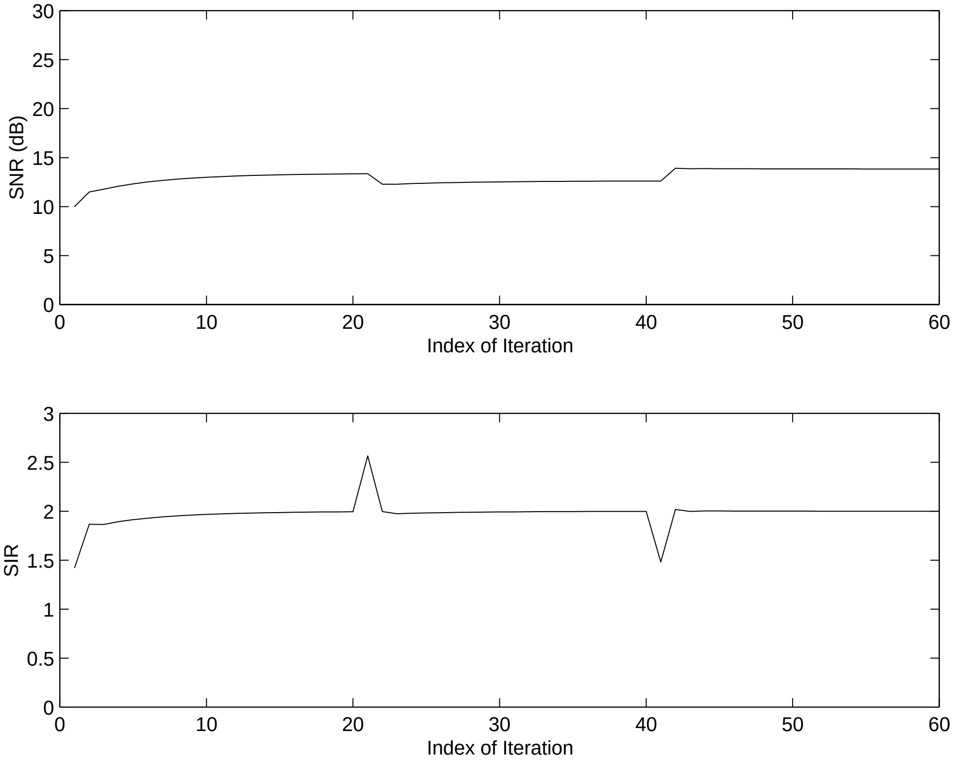

Figure 4.5 Power assignment and SIR for user 1 during iteration. $\tau_c = 20 \cdot t_{PC}$.

($M = 1$), since more energy is received using multiple antennas in the antenna array receiver.

We now study another case in which class II users have higher SIR requirement, $\gamma_1^* = 3$ dB and $\gamma_2^* = 6$ dB. The actual system capacity for $L = 3$, $\theta_d = 60°$ and the theoretical bound are plotted in Figure 4.7. For antenna array multiuser receiver ($M = 3$), at large power constraint (SNR = 30 dB) the actual system capacity is quite close to the theoretical bound. This again demonstrates that the theoretical bound is quite useful. At lower power constraint (SNR = 10 dB) capacity is reduced. The reduction when all users are in class I is about 1/5, while the reduction when all users are in class II is about 2/5. This is due to the higher SIR requirement (6 dB)

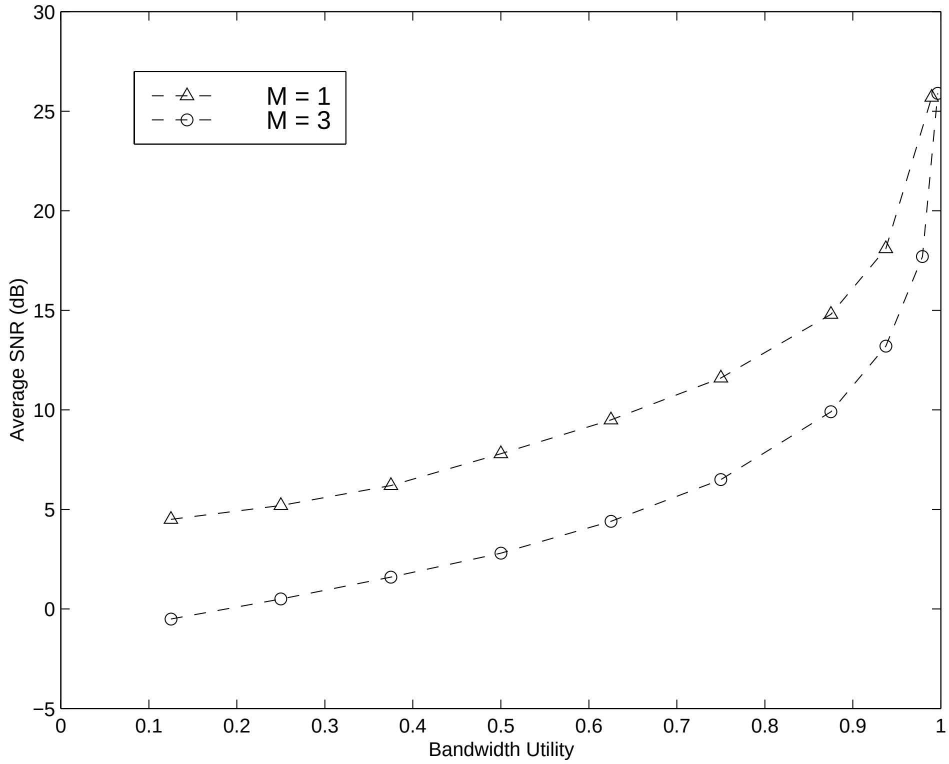

Figure 4.6 Average power vs. bandwidth utility, single class traffic.

for class II users and the lower power constraint (SNR = 10 dB). For single antenna multiuser receiver ($M = 1$), at large power constraint (SNR = 30 dB) the actual system capacity is quite close to the theoretical bound. At lower power constraint (SNR = 10 dB) capacity the capacity reduction when all users are in class I is about 1/2, while the reduction when all users are in class II is about 3/4. Therefore using multiple antennas helps to increase the bandwidth utility at lower power constraint.

We now study the power assignment for multiple classes of traffic. Consider an example $K_1 = 142$ and $K_2 = 120$ which is quite close to the theoretical bound on capacity. The power assignment of all the users solved by the iterative power control algorithm is depicted in Figure 4.8. The average SNR of class-I users is about 23 dB,

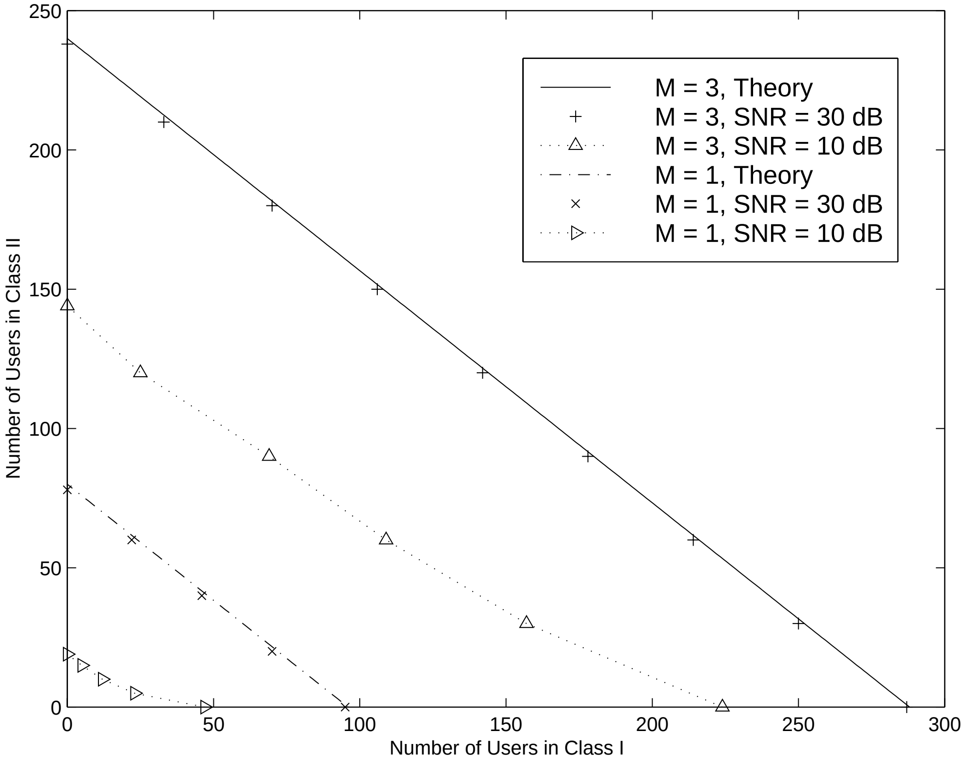

Figure 4.7 Capacity of dual-class CDMA system with antenna array multiuser receiver, single power constraint.

and the average SNR of class-II users is about 26 dB. This is consistent with the fact that the required SIR for class II users ($\gamma_2^* = 6$ dB) is 3 dB higher than that of class I users ($\gamma_1^* = 3$ dB). The range of SNRs in each class is about 5 dB. The variance of SNR among the users within each class is due to the different fading condition in channel and different cross-correlation of random codes. In fixed power control the received SNR is kept the same for all the users in each class, clearly this would cause a large variance in SIR among the users. This degrades quality of service and/or reduces system capacity. In contrast to fixed power control, adaptive power control dynamically adjust the SNR according to the fading condition in the channel and cross-correlation of codes such that SIR at the receiver is equal to the required SIR.

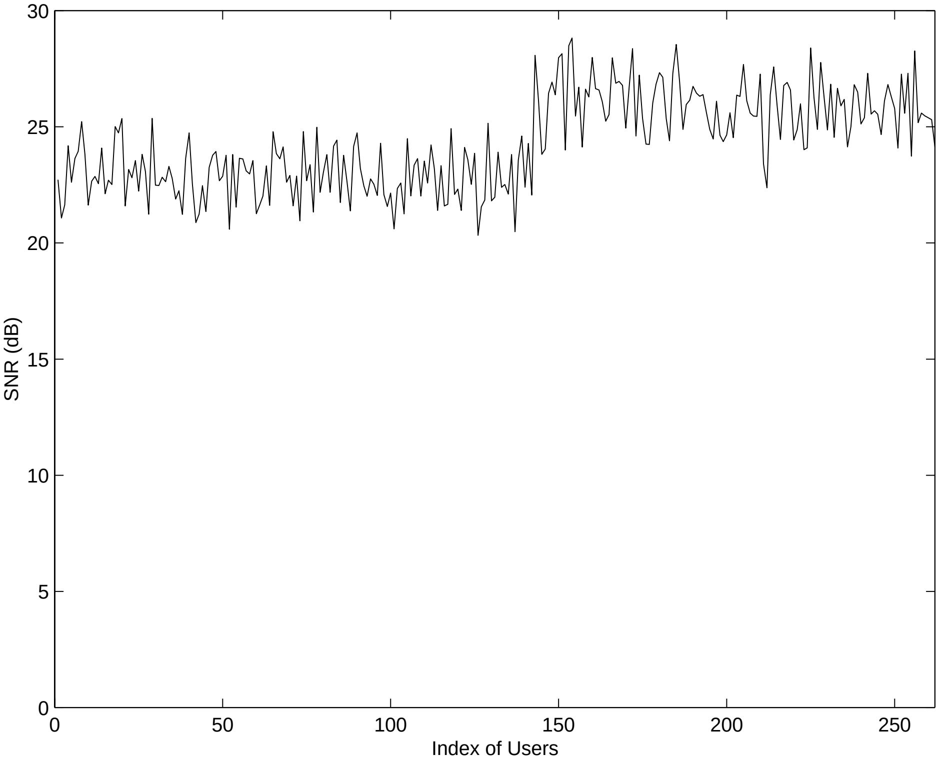

Figure 4.8 Power assignment of all the users. $K_1 = 142$, $K_2 = 120$.

We now study the power vs. load in system with multiple classes of traffic. The relation of average SNR for each class and bandwidth utility is depicted in Figure 4.9. Bandwidth utility is defined in (4.21). The average SNR for each class increases monotonically as the bandwidth utility increases. The average SNR of class-II users is about 3 dB higher than that of class-I users, which reflects the fact that the required SIR for class II users ($\gamma_2^* = 6$ dB) is 3 dB higher than that of class I users ($\gamma_1^* = 3$ dB). The plot shows that a relatively low power level ($SNR < 10$ dB) is sufficient for CDMA system with antenna array multiuser receiver to achieve reasonably high bandwidth utility ($\eta > 0.75$).

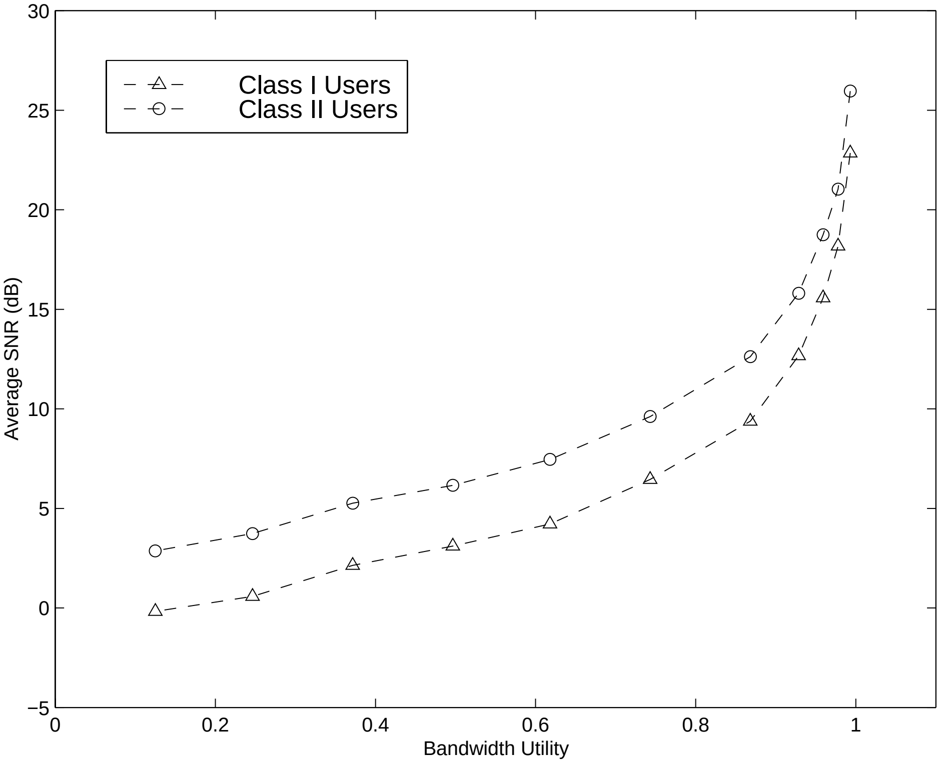

Figure 4.9 Average power vs. bandwidth utility, dual-class traffic.

In the above we have shown that the average SNR of class-II users is 3 dB higher than that of class-I users. This suggests using different power constraints for each class of users in a multi-class traffic system. The actual system capacity with dual power constraint and the theoretical bound are plotted in Figure 4.10. The power constraint for class I users are $SNR_1 = 30$ dB and $SNR_1 = 10$ dB respectively, and power constraint class II users are 3 dB higher than that of class I users. For antenna array multiuser receiver ($M = 3$), at large power constraint ($SNR_1 = 30$ dB, $SNR_2 = 33$ dB) the actual system capacity is quite close to the theoretical bound. At lower power constraint ($SNR_1 = 10$ dB, $SNR_2 = 13$ dB) capacity is reduced. The reduction is about 23% and it is the same for different proportion of class I and

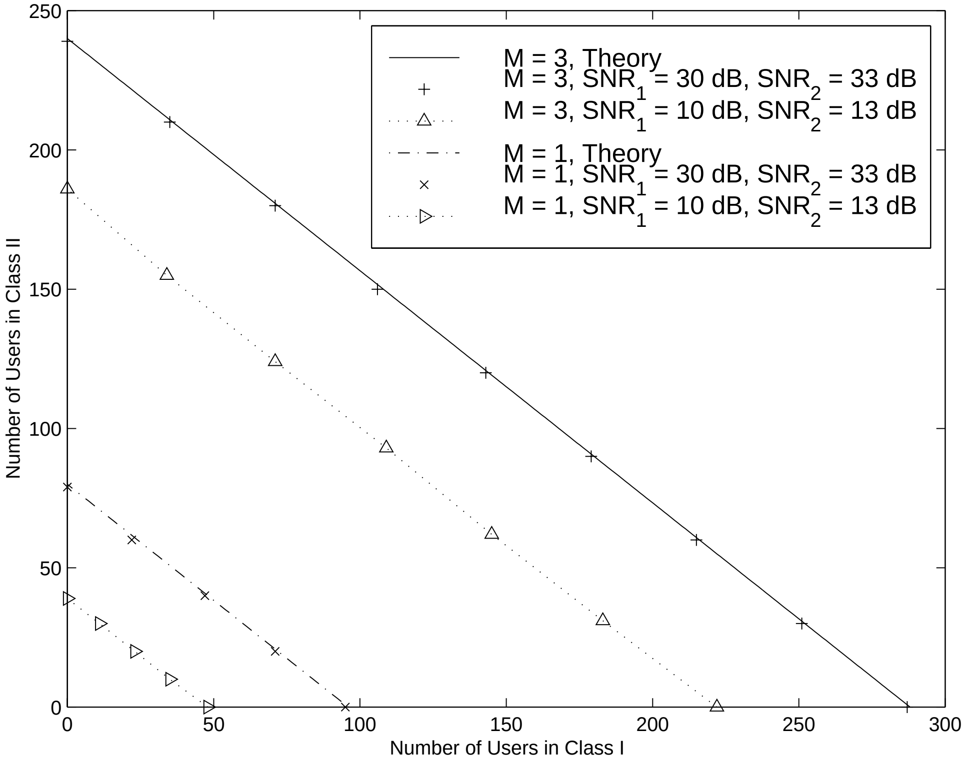

Figure 4.10 Capacity of dual-class CDMA system with antenna array multiuser receiver, dual power constraint.

class II users. Therefore using dual power constraint capacity can be simply described in terms of bandwidth utility. For example in this case bandwidth utility is about 0.77 for power constraint of $SNR_1 = 10$ dB and $SNR_2 = 13$ dB. For single antenna multiuser receiver ($M = 1$), at large power constraint ($SNR_1 = 30$ dB, $SNR_2 = 33$ dB) the actual system capacity is quite close to the theoretical bound. At lower power constraint ($SNR_1 = 10$ dB, $SNR_2 = 13$ dB) capacity is reduced by about 50% and bandwidth utility is about 0.5. Therefore using multiple antennas helps to increase the bandwidth utility at lower power constraint. The results here show that using dual power constraint the number of class II users that can be accommodated by the system is about 5/6 that of class I users for various power constraints, while the required SIR of class II users is twice that of class I users. Therefore using the antenna array multiuser receiver can increase the capacity of users with higher SIR requirement.

4.5 Summary

In this chapter we developed a new resource allocation scheme using adaptive power control and antenna array multiuser receiver. The scheme can support multiple classes of traffic with different target bit error rate and guarantee their quality of service requirements in multipath fading environment. Our approach is that both transmit power and receiver filter adapt to the time-varying fading channel state. An antenna array multiuser receiver that jointly processes received signal vectors sampled at chip rate from multiple antennas and maximizes the signal-to-interference ratio for each user is proposed. It is combined with adaptive power control based on required SIR to support multi-class traffic with different SIR requirements. A theoretical bound is derived to characterize capacity of CDMA system using the antenna array multiuser receiver. The degreee of freedom in CDMA system with antenna array multiuser receiver is the *product* of number of antennas and the spreading factor. Simulations show that actual system capacity in multipath fading environment is close to the theoretical bound at large power constraint. It is also demonstrated that the antenna array multiuser receiver is quite effective in increasing capacity of users with *higher* SIR requirement and *lower* power constraint.

Chapter 5

Call Admission Control in CDMA Cellular Network with Antenna Array Multiuser Receiver

Next generation wireless personal communication systems will support multiple classes of traffic with different quality of service requirements such as data rate and bit error rate. In the previous chapters we have developed a resource allocation scheme employing joint adaptive power control and antenna array multiuser receiver to support multi-class traffic with diverse QoS requirements in wireless CDMA networks. Due to the statistical multiplexing inherent in CDMA system there is a tradeoff between the system capacity and the level of quality of service. As more and more users access the system at the same time, the quality of communication link for individual user deteriorates due to excessive multiple access interference. In order to guarantee the quality of service for all the traffic in a cellular system, call admission control (CAC) must be applied to control the number of users in each cell such that an appropriate level of communication quality can be maintained. When a new call request is received, admission control algorithm should decide whether it should be admitted into the system or not. If it is expected that after admitting the new call into the system the QoS of all the users can still be guaranteed, then the new call should be admitted. If it is expected that after admitting the new call into the system users' QoS requirements are likely to be violated then the new call request should be blocked. CAC schemes that are too conservative tend to admit less number of users than that can be accommdated by the system, therefore under-utilize the precious bandwidth resource. CAC schemes that are too optimistic tend to admit more number of users than that can be accommdated by the system, therefore violate users' QoS requirements. A good admission control scheme should achieve high capacity utilization without violating QoS guarantees. Existing works on call admission control in CDMA systems are interference-based or SIR-based and apply only to systems with conventional matched-filter receiver, fixed power control and single-class traffic. Our goal is to develop an admission control scheme that supports multiple classes of traffic with different QoS requirements and incorporates adaptive power control and antenna array multiuser receiver.

In this chapter we propose an admission control scheme for CDMA cellular system using joint adaptive power control and antenna array multiuser receiver. A relation of cell capacity and other-cell interference level is first established. Then admission control is implemented in each cell based on the estimation of other-cell interference. Performance of the CAC scheme is evaluated by comparing the cell capacity determined by the admission control algorithm and actual system capacity in the simulation. The rest of the chapter is organized as follows: In Section 5.1 the CDMA cellular system model is described. Section 5.2 describes the proposed admission control algorithm. In Section 5.3 the CDMA cellular system is simulated and numerical results on system capacity are presented. The admission control scheme is implemented in simulation and performance of the algorithm is evaluated. The main results are summarized in Section 5.4.

5.1 Cellular System Model

In CDMA cellular system, the whole service area is divided into cells and each cell is served by a base station. We consider a direct-sequence CDMA system with BPSK modulation, and focus on synchronous and single-data-rate transmission in the uplink. Each base station is equiped with a multiuser antenna array receiver in the uplink. It is assumed that the multiuser antenna array receiver does not have knowledge of the effective spatial-spreading signatures of other-cell users, and interference from all other-cell users is modeled as white gaussian noise and included in the noise term at the receiver. This is justified considering that total other-cell interference is the sum of a large number of users with independent and random spreading signatures and the complex random fading channel. User mobility and call handoff are not modeled here.

Considering the ith cell in the cellular system. There are K users in the cell. The received signal vector sampled at chip rate in a symbol period, i.e. chip matched-filter output signals from the M antenna elements are processed jointly at the multiuser antenna array receiver. Concatenating signal vectors from the M antenna elements we can define a joint signal vector $\mathbf{r} \equiv [(\mathbf{r}^{(1)})^H, \cdots, (\mathbf{r}^{(M)})^H]^H$. It can be written as

$$\mathbf{r} = \sum_{k=1}^{K} A_k b_k \mathbf{a_k} + \mathbf{n_I} + \mathbf{n_0}, \tag{5.1}$$

where A_k, b_k and $\mathbf{a_k}$ are the received amplitude, the transmitted bit and the effective spatial-spreading signature for user k respectively. The terms $\mathbf{n_I}$ and $\mathbf{n_0}$ are the other-cell interference and thermal noise respectively. The other-cell interference is modeled as white Gaussian noise and the interference power is given by

$$P_I = \sum_{k' \subset j, j \neq i} q_{k'} G_{k',i}, \tag{5.2}$$

where $q_{k'}$ is the transmit power of user k', and $G_{k',i}$ is the path gain from user k' to the base station of the ith cell. In the multiuser antenna array receiver a spatial-spreading filter with coefficients $\mathbf{c}_k$ is used to demodulate user k and the receiver statistic is

$\mathbf{c}_k^H\mathbf{r}$. The filter coefficients $\mathbf{c}_k$ is selected to maximize the SIR of user k,

$$\mathbf{c}_k = \frac{\mathbf{Z}_k^{-1}\mathbf{a}_k}{\mathbf{a}_k^H\mathbf{Z}_k^{-1}\mathbf{a}_k}, \tag{5.3}$$

where $\mathbf{Z}_k$ is the covariance matrix of the interference to user k defined as

$$\mathbf{Z}_k \equiv \sum_{k' \neq k} P_{k'}\mathbf{a}_{k'}\mathbf{a}_{k'}^H + (P_I/N + \sigma^2)\mathbf{I}. \tag{5.4}$$

Notice here due to the despreading effect the othercell interference is reduced by a factor of N, where N is the spreading factor. The adaptive power control algorithm adjusts the transmit powers so that the SIR at the receiver exceeds or equal to the required SIR for all the users in the cell. This is implemented by the iterative power control scheme described in Chapter 4. In a cellular system the joint adaptive power control and antenna array multiuser receiver is implemented in each cell independently and no intercell signaling is required.

5.2 Admission Control Algorithm

In order to establish an admission control scheme we first look at capacity of a cellular system. The question of cellular system capacity can be stated as: What is the maximum number of users in each cell for which there exists power assignment that SIR requirements of all the users in the cellular system can be met. For a single cell system it is proved that capacity can be characterized by a theoretical bound in (4.13). It is also shown that the actual capacity in simulation is quite close to the theoretical bound given large power constraints. For a cellular system capacity of a cell is affected by interference from users located in neighboring cells. Cell capacity is expected to be less than that of single cell system due to the othercell interference. The heavier the neighboring cells are loaded, the stronger the othercell interference is, therefore the less users can be accommodated in the current cell. Capacity in cellular system can be evaluated via simulation. Given a number of users with required SIR distributed in the cellular system, an adaptive power control algorithm is used to find out whether there exists feasible transmit power assignment that all the users' SIR requirements can be met simultaneously. The set of maximum number of users in each cell for which SIR requirements of all the users can be met is said to be the actual system capacity.

In a real cellular system a simple and easy to implement admission control algorithm is needed to decide whether to accept a new call request based on the current load in cellular system. In order to do this it is desirable to know the cell capacity before admission rather than running the whole system simulation after admitting the new call. We propose here an CAC scheme based on estimating other-cell interference. It includes the following steps:

1. A relation of cell capacity and other-cell interference power is first established for given required SIR, mobile transmit power contraint, cell size and propagation model. It is obtained via simulation of a single cell with various level of other-cell interference power.

2. In real cellular system admission control is implemented at each cell in a distributive way. Each cell estimates other-cell interference power and determines the current cell capacity based on the established relation.

3. When a new call request arrives in a cell, admission control decision is made by comparing current cell capacity and current number of users in the cell. If current cell capacity exceeds current number of users in the cell, the new call is admitted into the current cell. Otherwise the new call request is rejected.

5.3 Simulation and Numerical Results

The proposed CAC scheme is demonstrated via simulation of a CDMA cellular system. Assume a bandwidth of 4.096 MHz is allocated for the wideband CDMA system. The transmission symbol rate is 64 kbps, corresponding to a spreading factor of $N = 64$. The users' spreading sequences are independently and randomly chosen. The cellular system is modeled as a 5×5 array of cells with 25 cells in total. Each cell is a 2 km × 2 km square. Users are uniformly distributed in the cell. A propagation loss model in macro cell environment is used in the simulation [79]. The multipath fading channel is modeled as follows: $L = 3$ paths for each user, the angle of arrival (AOA) of these paths are randomly distributed within $[\theta_k - \theta_d/2, \theta_k + \theta_d/2]$, where θ_k is the AOA of user k and $\theta_d = 60^\circ$ is the dispersion angle of the multipaths for each user. The power is equally distributed among the L paths and each path has a complex random variable coefficient due to the fading effect. We assume a slowing fading channel, i.e. the period during which channel is nearly static τ_c is much longer than the power update interval t_{PC}. In the simulation a uniform circular array (UCA) with $M = 3$ antenna elements is used in the receiver. We consider a "hotspot" scenario in which the central cell is heavily loaded, and focus on admission control in the central cell. We assume that all the surrounding cells have the same number of users, i.e. they are equally loaded. For simplicity we also assume single-class traffic in the surrounding cells. The required SIR is $\gamma^* = 3$ dB and the transmit power constraint for each user is $q_x = 200$ mW. For the central cell we assume dual-class traffic with class I users have required SIR of $\gamma_1^* = 3$ dB and transmit power constraint of $q_{x1} = 200$ mW, and class II users have required SIR of $\gamma_2^* = 6$ dB and transmit power constraint of $q_{x2} = 400$ mW. Notice that the transmit power constraint of class II users is twice that of class I users, since the required SIR for class II users is twice that of class I users.

The cellular system being simulated is illustrated in Figure 5.1. In this case the number of users in the central cell is $K_{cent} = 200$, while the number of users in each surrouding cell is $K_{surr} = 60$. We first consider a simple case in which all the users in the central cell is class I users. Capacity in the central cell vs. load in surrounding cell is obtained via simulation and depicted in Figure 5.2. It is shown clearly that as the load in surrounding cells becomes larger, capacity in the central cell decreases. When there are no users in the surrounding cells the capacity in the central cell is 284 users, which is quite close to that given by the theoretical bound (288 users). When there are 96 users in each surrounding cell the capacity in the central cell is 104 users, while when there are 98 users in each surrounding cell the capacity in the central cell is 78 users, which is no longer a 'hotspot' scenario. Therefore for uniform traffic distribution in which each cell has nearly the same number of users, the cell capacity is about 96 users per cell, which is about 1/3 of that in single cell system.

Now we turn to the case of dual-class traffic. Cell capacity at different levels of other-cell interference power is depicted in Figure 5.3. Other-cell interference power is expressed in terms of interference-to-noise power ratio denoted as P_i/P_n. As one can see cell capacity decreases as the other-cell interference becomes larger. To better understand cell capacity for multi-class traffic system, we calculated capacity bandwidth utility as defined in (4.21. The bandwidth utility vs. othercell interference are depicted in Figure 5.4 for three cases: class I users only, class II users only and both classes I and II users. The bandwidth utility in these cases are quite close to each other, suggesting that it can be used to characterize cell capacity for all possible combination of number of users in classes I and II. The average bandwdith utility for all possible combination of number of users in classes I and II is calculated and plotted

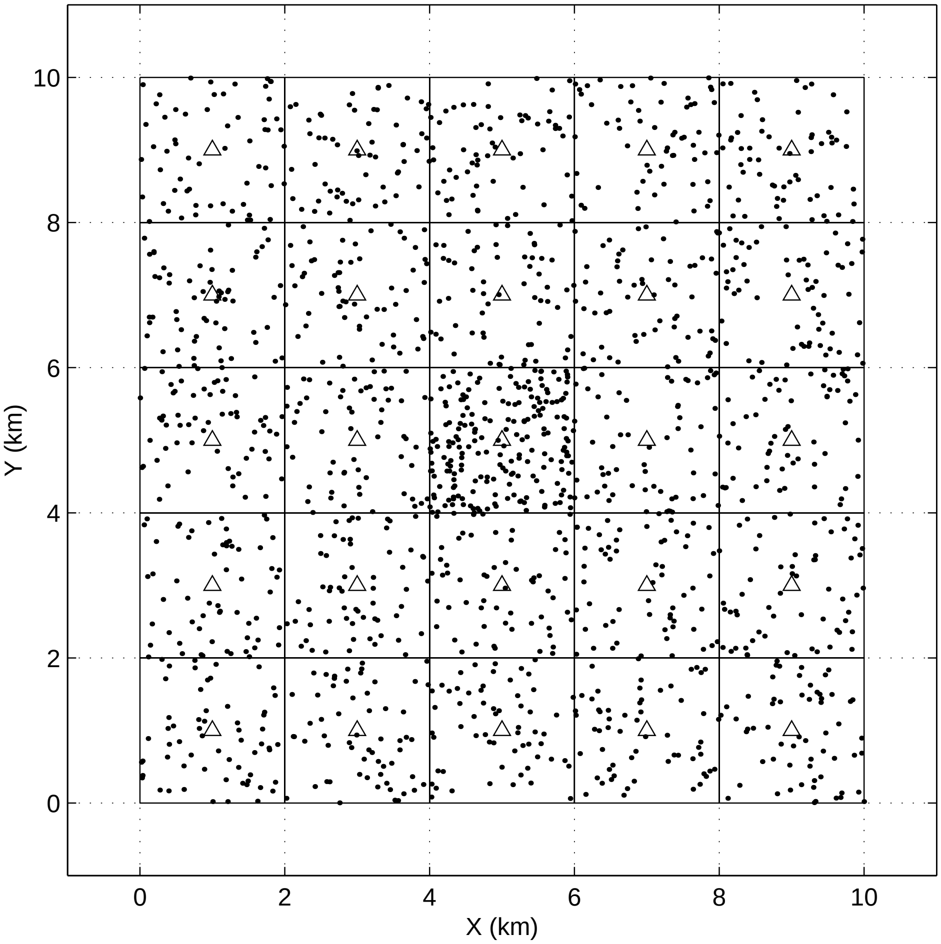

Figure 5.1 CDMA Cellular System. $K_{cent} = 200$, $K_{surr} = 60$

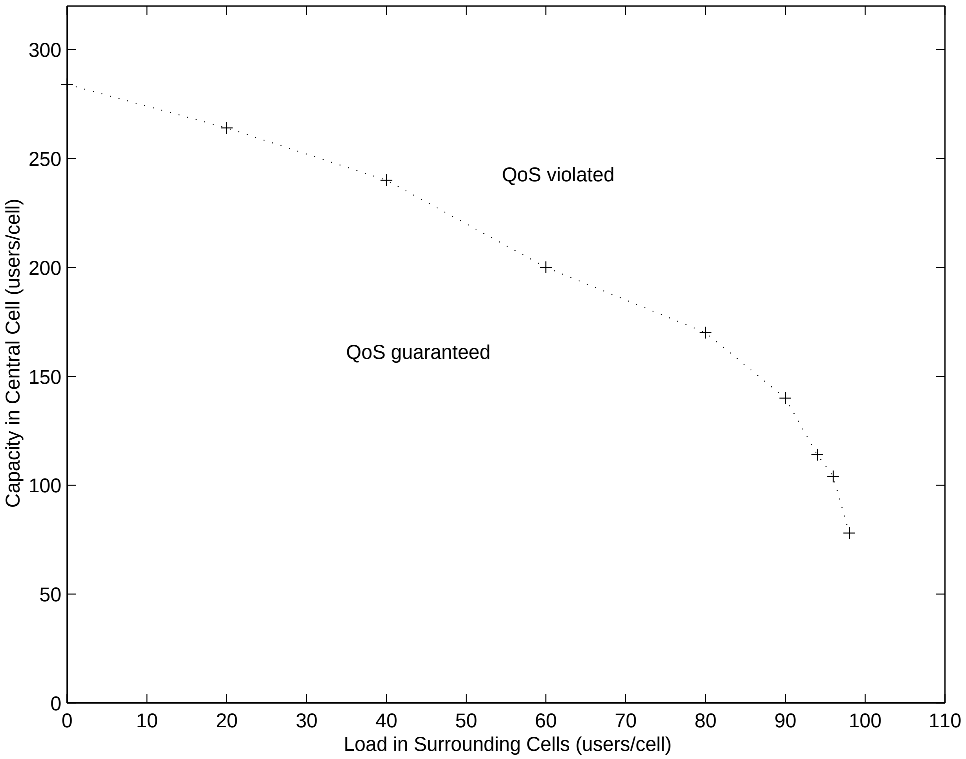

Figure 5.2 Capacity in central cell vs. load in surrounding cells, single class traffic

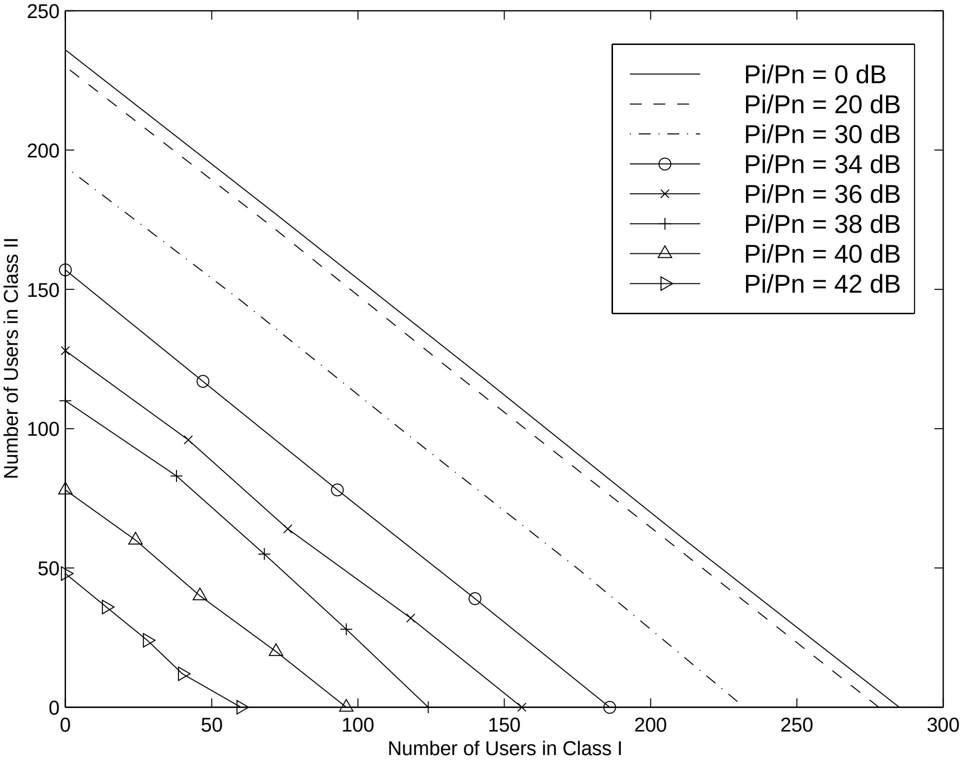

Figure 5.3 Cell capacity vs. othercell interference, dual-class traffic

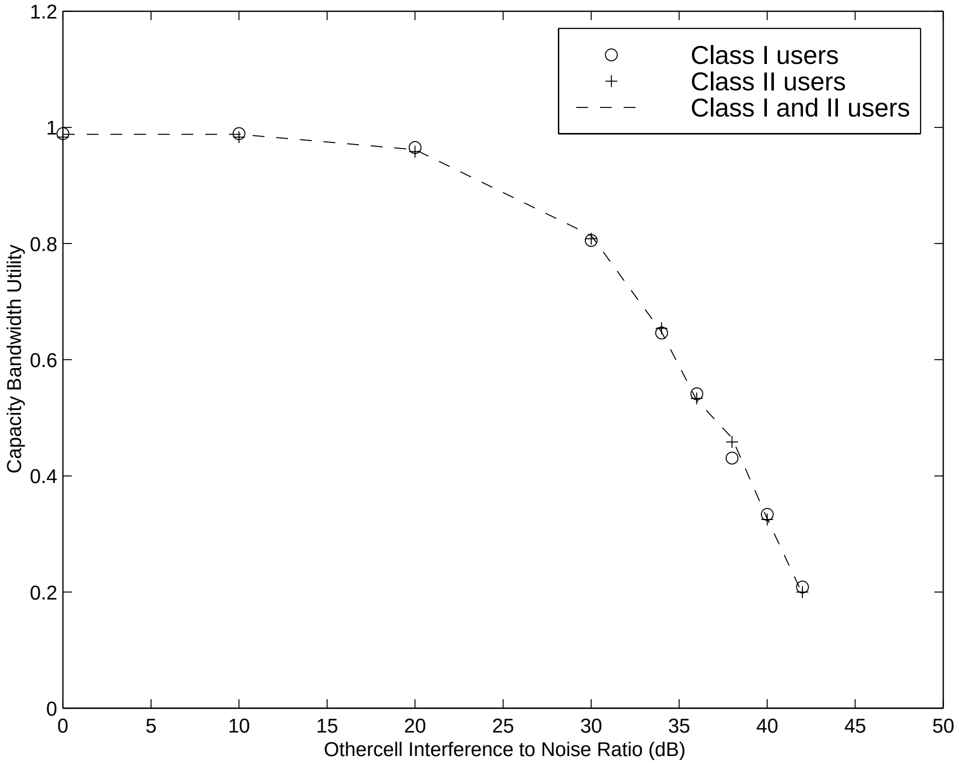

Figure 5.4 Capacity bandwidth utility vs. othercell interference, dual-class traffic

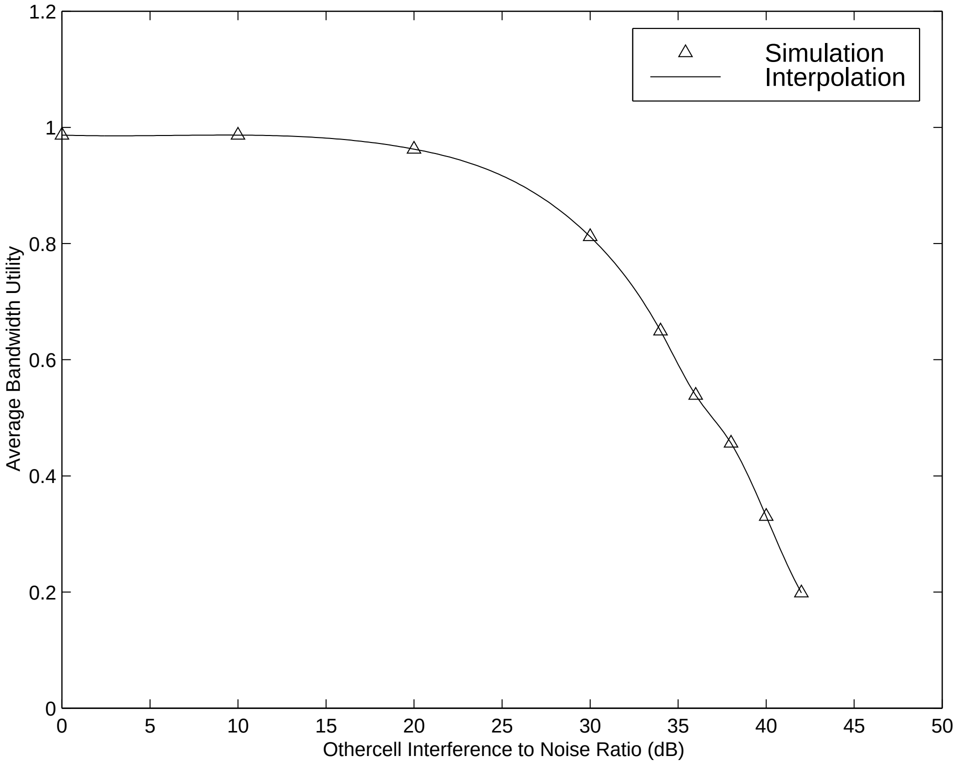

Figure 5.5 Average bandwidth utility vs. othercell interference

as a function of othercell interference in Figure 5.5. The average bandwidth utility decreases as the othercell interference becomes larger. When othercell interference level is low ($P_i/P_n < 20$ dB) the bandwidth utility is close to 1. While when the othercell interference level rises to $P_i/P_n = 40$ dB, the bandwidth utility is only 0.33. Therefore we have established a relation of capacity bandwidth utility and othercell interference level and this relation will be used in our admission control algorithm.

In a real cellular system admission control is implemented in each cell, for simplicity in the simulation we assume there are fixed number of users in each surrounding cell and focus on admission control in the central cell. We only consider number of active users in the cell so call arrival and call termination are not modeled. For a certain load in the surrounding cells, new call request is generated in the central cell. The base station estimates the othercell interference power and find out the capacity bandwidth utility based on the relation depicted in Figure 5.5. The base station then calculates the current bandwidth utility defined in (4.21) based on the current number of users in classes I and II. The base station also calculates the new call bandwidth utility defined as

$$\eta_{nc} \equiv \frac{1}{MN}\frac{\gamma_k^*}{1+\gamma_k^*}, \tag{5.5}$$

where γ_k^* is the required SIR for the new call. The CAC algorithm makes decision on whether to admit the new call by comparing the capacity bandwidth utility (η_0) with the sum of current bandwidth utility (η_1) and new call bandwidth utility (η_{nc}). If $\eta_0 > \eta_1 + \eta_{nc}$ the new call is admitted, otherwise the new call is blocked.

The performance of the admission control algorithm is evaluated by comparing the capacity determined by the CAC algorithm and the actual capacity in the simulation. We keep adding users in the central cell until the CAC algorithm rejects the new call. The maximum number of users admitted is the capacity determined by the CAC

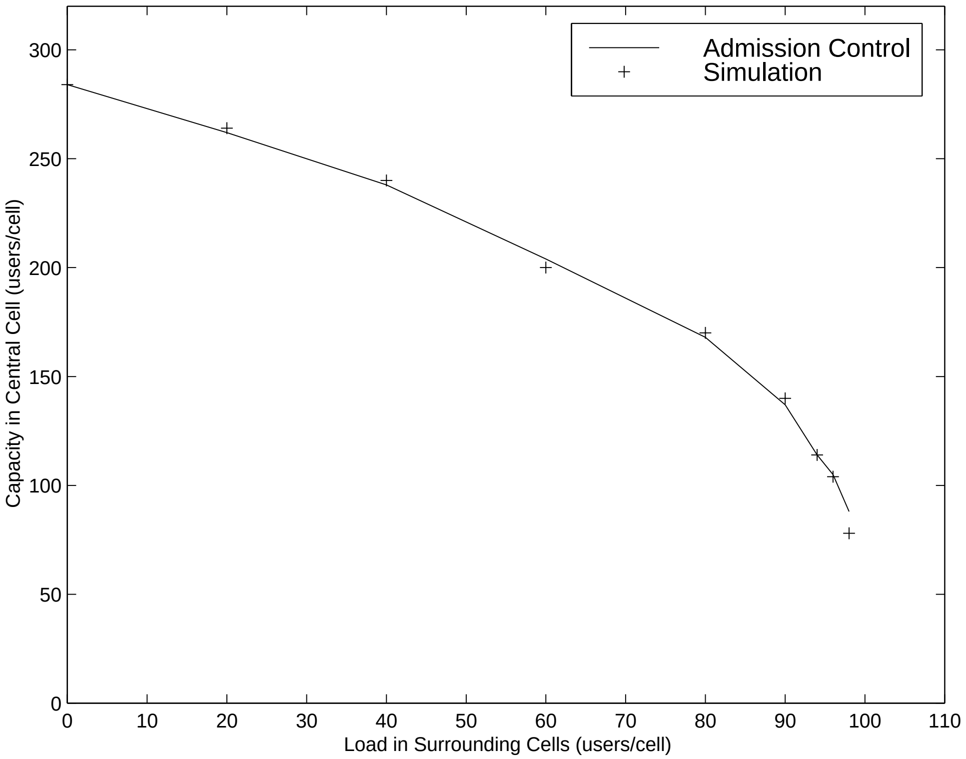

Figure 5.6 Capacity in central cell: admission control vs. simulation, single class traffic

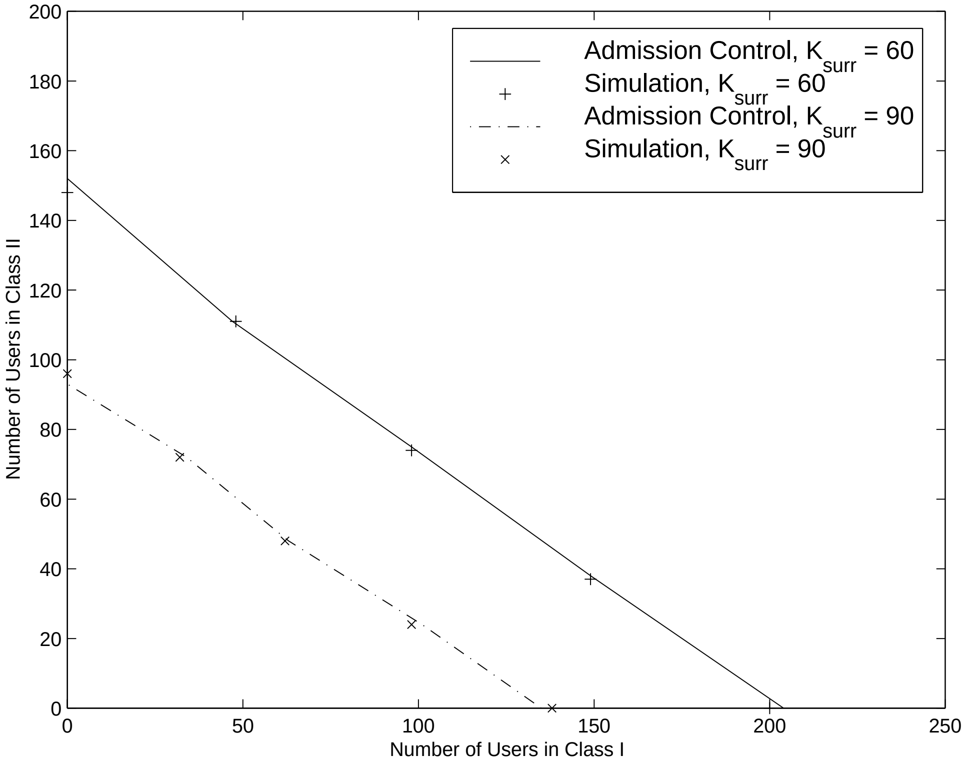

Figure 5.7 Capacity in central cell: admission control vs. simulation, dual-class traffic

algorithm. The capacity determined by the CAC algorithm versus load in surrounding cells is depicted in Figure 5.6 for the case of single-class traffic in the central cell. For comparison the actual capacity in the central cell given by simalation is also plotted. They are quite close to each other, which indicates that the CAC algorithm is accurate. The difference is mainly due to the randomness in fading channel. In the simulation it is observed that variation of the channel status due to fading can cause capacity to fluctuate about couple of users. Capacity is said to be achievable only if feasible power assignments exist such that users' SIR requirements can be met for a high probability, usually 90% among all the random fading status. It is noticed that capacity determined by admission control is larger than that of simulation when load in surrounding cells is quite heavy (98 users/cell). In this case the admission control algorithm accepts more users into the central cell than the system can accommodate, therefore users' QoS is violated. This is due to the fact that surrounding cells are so heavily loaded that the central cell is no longer a 'hotspot', i.e. congestion happens at surrounding cells rather than the central cells. Therefore admission control in the central cell only does not help guarantee the users' QoS in the cellular system. This situation however shall not happen in real cellular system because there admission control is also implemented in the surrounding cells thus overloading in the surrouding cells is avoided and users' QoS can be guaranteed. In the case of dual-class traffic in the central cell, capacity determined by the CAC algorithm as well as capacity obtained via simulation is depicted in Figure 5.7. We can see that the capacity determined by the CAC algorithm is close to that in simulation at various load in surrounding cells (60 users/cell and 90 users/cell). Therefore the admission control is accurate for multi-class traffic as well.

5.4 Summary

In this chapter we developed an admission control scheme for CDMA cellular system that supports multiple classes of traffic with different QoS requirements and incorporates adaptive power control and antenna array multiuser receiver. Joint adaptive power control and antenna array multiuser receiver are used to guarantee users' QoS requirements in terms of required SIR and increase system capacity significantly. A relation of cell capacity and othercell interference level is first established via simulation. For multi-class traffic system a notion of bandwidth utility is used to characterize capacity in the admission control algorithm. The CAC scheme is then implemented distributively in each cell based on estimation of othercell interference. In our simulation it is demonstrated that the CAC scheme can adapt to various traffic distribution. Capacity determined by the CAC algorithm agrees well with that given by simulation. Therefore it can achieve high bandwidth utilization while guarantee QoS requirements of all the users.

Chapter 6

Conclusions

In this thesis we developed a resource allocation framework for wireless CDMA networks that support multi-class traffic with different data rates and bit error rate requirements. We proposed a new resource allocation scheme using joint adaptive power control and antenna array multiuser receiver in multipath fading system. In this scheme both transmit power and receiver filter adapt to time-varying fading channel state. By dynamically assigning users appropriate transmit power and receiver filter, the scheme can guarantee users' diverse QoS requirements and significantly improve quality and capacity of the system. We derived theory for abstraction of bandwidth resource and characterization of system capacity for multi-class traffic in multipath fading system. Bandwidth resource allocated to a user can be abstracted as "effective bandwidth", determined by the user's source data rate and target bit error rate. Capacity in multipath fading system can be characterized by a theoretical bound. Simulation results demonstrate the effectiveness of the proposed resource allocation scheme and substantiate the theory.

In Chapter 3 we developed a resource allocation scheme using adaptive power control and multirate multiuser receiver to support multi-class traffic. A multirate multiuser receiver that maximizes the signal-to-interference ratio (SIR) for each symbol is proposed for multirate CDMA system. It is combined with adaptive power control based on required SIR to provide different quality of service for multiple-data-rate traffic. A theoretical bound is derived to characterize the capacity of multi-class

CDMA system using the multirate multiuser receiver. Simulations show that actual system capacity in multipath fading environment is close to the theoretical bound at large power constraint. The multirate multiuser receiver can achieve significantly larger capacity for users with higher source data rate and lower target bit error rate than conventional matched-filter receiver.

In Chapter 4 we developed a resource allocation scheme using adaptive power control and antenna array multiuser receiver to support multi-class traffic in CDMA system. An antenna array multiuser receiver that jointly processes received signal vectors sampled at chip rate from multiple antennas and maximizes the signal-to-interference ratio for each user is proposed. It is combined with adaptive power control based on required SIR to support multi-class traffic with different SIR requirement. A theoretical bound is derived to characterize capacity of CDMA system using the antenna array multiuser receiver. The degreee of freedom in CDMA system using the antenna array multiuser receiver is the product of number of antennas and the spreading factor. Simulations show that actual system capacity in multipath fading environment is close to the theoretical bound at large power constraint. The antenna array multiuser receiver can provide large capacity for users with higher SIR requirement and achieve high bandwidth utility at lower power constraints.

In Chapter 5 we proposed a new call admission control scheme for CDMA cellular system that incorporates adaptive power control and antenna array multiuser receiver and supports multi-class traffic. The scheme is based on estimation of other-cell interference and implemented distributively in each cell. The scheme can adapt to various traffic distribution. Capacity determined by the admission control agrees well with the actual system capacity in the simulation. The scheme can achieve high bandwidth utilization and guarantee QoS requirements of all the users.

6.1 Future Work

The resource allocation problem in wireless CDMA networks include issues related to three different problems:

- power control, receiver structure, abstraction of bandwidth resources and characterization of system capacity for multi-class traffic with different data rates and bit error rate requirements.
- packet access control and scheduling of heterogeneous traffic such as CBR, VBR, packet data, etc.
- call admission control and handoff control in CDMA cellular systems.

This thesis provides a solution to the resource allocation problem in multi-class traffic system, as well as the admission control problem in cellular system. In order to guarantee users' QoS requirements in terms of delay for real time traffic and throughput for non real time traffic in CDMA networks, it is necessary to develop an efficient access control and scheduling scheme. As a matter of fact, the results on abstraction of bandwidth resource in this thesis can greatly simplify this task. We can view the CDMA bandwidth as a "bandwidth pipeline" and calculate the bandwidth that needs to be allocated to a packet based on its data rate and bit error rate requirement. We can then schedule the packets by filling the bandwidth pipeline and giving priority to packets with more stringent delay requirements.

In the thesis it is assumed that power control is perfect, i.e. it always adapts to variation of the channel and keeps the SIR at a constant required level. While this is realistic when fading is slow, it is interesting to study the resource allocation problem in fast fading environment. There the SIR at the receiver is not constant but randomly distributed due to the error in power control. It is possible to extend the resource allocation scheme in the thesis to this case using adaptive power control based on the mean value of the SIR.

The cellular system demonstrated in the thesis is in a macrocell environment with cell dimension of several kilometers. The propagation loss model is also that of macrocell system. An interest question is how this system scales, i.e. what is the capacity of cellular system in a microcell or picocell environment with cell dimension of several hundred meters to tens of meters. Our simulation program provides a tool to study this problem using different propagation models and simulation parameters. Since the proposed call admission control scheme is based on the *estimation* of other-cell interference, it is expected to have good performance in various cellular systems including macrocell, microcell, and picocell environment.

This thesis proposes a call admission control scheme for CDMA cellular networks using adaptive power control and antenna array multiuser receiver. While the work provides a solution to the admission control problem in multi-class traffic cellular system, it does not model user mobility and time varying dynamics of the traffic. It would be ideal to incorporate these effects and extend the admission control scheme to a more realistic scenario. It is also interesting to develop a joint admission and handoff control scheme to better adapt to the dynamic and non-uniformly distributed traffic in CDMA cellular networks.

In this thesis we focus on solving resource allocation problems in the uplink (from mobile to base station) transmission. Traditionally this has been a bottleneck in the performance of wireless networks due to the difficulties in keeping users synchronized at the base station, the limited handset power and battery life, and the large overhead in packet access control and scheduling. In next generation wireless networks traffic in the downlink (from base station to mobile) is likely to increase signicantly due to the need to access and download information from the internet. Meanwhile performance of uplink transmission will be greatly improved using performance enhancing techniques such as the antenna array multiuser receiver developed in this thesis. Therefore downlink could be a bottleneck and it is desirable to enhance its performance using various technologies. A resource allocation scheme using joint transmit power control and beamforming using antenna array transmitter at the base station could be the one of the solutions.

Bibliography

[1] ETSI SMG2, "The ETSI UMTS Terrestrial Radio Access (UTRA) ITU-R RTT Candidate Submission," Tech. Rep., European Telecommunications Standard Institution (ETSI), 1998.

[2] TIA TR-45.5, "The cdma2000 RTT Candidate Submission," Tech. Rep., U.S. Telecommunication Industry Association (TIA), 1998.

[3] ARIB IMT-2000 Study Committee, "Japan's Proposal for Candidate RTT on IMT-2000: W-CDMA," Tech. Rep., Association of Radio Industires and Businesses (ARIB), 1998.

[4] Chinese Academy of Telecommunication Technology, "TD-SCDMA RTT for IMT-2000," Tech. Rep., Telecommunication Administration of China, 1998.

[5] TTA, "Global CDMA I/II for IMT-2000 RTT System Description," Tech. Rep., Korean TTA, 1998.

[6] R.D. Carsello et al, "IMT-2000 Standards: Radio Aspects," *IEEE Personal Communications*, August 1997.

[7] R. Randya et al, "IMT-2000 Standards: Network Aspects," *IEEE Personal Communications*, August 1997.

[8] K. Buchanan et al, "IMT-2000: Service Provider's Perspective," *IEEE Personal Communications*, August 1997.

[9] F. Leite et al, "Regulatory Considerations Relating to IMT-2000," *IEEE Personal Communications*, August 1997.

[10] TIA/EIA/IS-95-A, "Mobile Station - Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," Tech. Rep., Telecommunications Industry Association, 1995.

[11] ANSI J-STD-008, "Personal Station - Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum PCS System," Tech. Rep., ANSI, 1995.

[12] K.S. Gilhousen et al, "On the Capacity of a Cellular CDMA System," *IEEE Trans. Veh. Techno.*, vol. 40, no. 2, pp. 303, 1991.

[13] A.M. Viterbi and A.J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System," *IEEE. J. Select. Areas. Commun.*, vol. 11, no. 6, pp. 892, 1993.

[14] A.J. Viterbi et al, "Soft Handoff Extends CDMA Cell Coverage and Increases Reverse Link Capacity," *IEEE. J. Select. Areas. Commun.*, vol. 12, no. 8, pp. 1281, 1994.

[15] A.J. Viterbi, "The Orthogonal-Random Waveform Dichotomy for Digital Mobile Personal Communication," *IEEE Personal Communications*, , no. 1, 1994.

[16] R. Padovani, "Reverse Link Performance of IS-95 Based Cellular Systems," *IEEE Personal Communications*, , no. 3, 1994.

[17] C. Sengupta, J.R. Cavallaro, and B. Aazhang, "Maximum Likelihood Multipath Channel Parameter Estimation in CDMA Systems using Antenna Arrays," in *CISS*, 1998.

[18] C. Sengupta, J.R. Cavallaro, and B. Aazhang, “Maximum Likelihood Estimation of Multipath Channel Parameters in CDMA Systems,” *Submitted to IEEE Trans. Comm.*, 1998.

[19] R. Yates, “A Framework for Uplink Power Control in Cellular Radio Systems,” *IEEE. J. Select. Areas. Commun.*, vol. 13, no. 7, pp. 1341, 1995.

[20] S. Ulukus and R. Yates, “Stochastic Power Control for Cellular Radio Systems,” *Submitted to IEEE Trans. Comm.*, 1996.

[21] A. Sampath, P. Kumar, and J. Holtzman, “Power Control and Resource Management for a Multimedia CDMA Wireless System,” Tech. Rep., WINLAB, Rutgers Univeristy, 1995.

[22] S. Hanly, “Capacity and Power Control in Spread Spectrum Macrodiversity Radio Networks,” *IEEE Trans. Comm.*, vol. 44, no. 2, pp. 247, 1996.

[23] S. Hanly, “An Algorithm for Combined Cell-Site Selection and Power Control to Maximize Cellular Spread Spectrum Capacity,” *IEEE. J. Select. Areas. Commun.*, vol. 13, no. 7, pp. 1332, 1995.

[24] J. Qiu and J. Mark, “A Dynamic Load Sharing Algorithm Through Power Control in Cellular CDMA,” in *GLOBECOM*, 1998.

[25] A. Duel-Hallen, J. Holtzman, and Z. Zvonar, “Multiuser Detection for CDMA Systems,” *IEEE Personal Communications*, p. 46, Apr. 1995.

[26] S. Moshavi, “Multi-User Detection for DS-CDMA Communications,” *IEEE Communications Magazine*, p. 124, Oct. 1996.

[27] S. Verdu, “Demodulation in the Presence of Multiuser Interference: Progress and Misconceptions,” in *Intelligent Methods in Signal Processing and Communications*, pp. 15–44. Birkhauser, 1997.

[28] U. Madhow and M. L. Honig, “MMSE Interference Suppression for Direct-Sequence Spread-Spectrum CDMA,” *IEEE Trans. Commun.*, vol. 42, no. 12, pp. 3178, Dec. 1994.

[29] M. L. Honig and H. V. Poor, “Adaptive Interference Suppression,” in *Wireless Communications: Signal Processing Perspectives*, p. 64. Prentice Hall, 1998.

[30] H. V. Poor and S. Verdu, “Probability of Error in MMSE Multiuser Detection,” *IEEE Trans. on Information Theory*, vol. 43, no. 3, pp. 858, MAY 1997.

[31] A. M. Sayeed, A. Sendonaris, and B. Aazhang, “Multiuser Detection in Fast Fading Multipath Environments,” *in preparation*, 1998.

[32] M. Latva-aho and M. Juntti, “Modified Adaptive LMMSE Receiver for DS-CDMA systems in Fading Channels,” in *PIMRC*, 1997.

[33] Z. Zvonar, “Multiuser Detection in Single-Path Fading Channels,” *IEEE Trans. Commun.*, vol. 42, no. 2/3/4, pp. 1729, 1994.

[34] Z. Zvonar, “Combined Multiuser Detection and Diversity Reception for Wireless CDMA Systems,” *IEEE Trans. Veh. Technol.*, vol. 45, no. 1, pp. 205, 1996.

[35] D. Tse and O. Zeitouni, “Performance of Linear Multiuser Receivers in Random Environments,” *Submitted to the IEEE Trans. Info. Theory*, 1998.

[36] M. Honig, U. Madhow, and S. Verdu, “Blind Adaptive Multiuser Detection,” *IEEE Trans. Info. Theory*, vol. 41, no. 4, pp. 944, 1995.

[37] M. Juntti, *Multiuser Demodulation for CDMA Systems in Fading Channels*, Ph.D. thesis, University of Oulu, 1997.

[38] A. Hottinen, H. Holma, and A. Toskala, "Multiuser Detection for Multirate CDMA Communications," in *PIMRC*, 1996.

[39] S. Buzzi, M. Lops, and A.M. Tulino, "MMSE Multiuser Detection for Asynchronous Dual-Rate Direct Sequence CDMA Communications," in *GLOBECOM*, 1998.

[40] J. Ma and H. Ge, "Modified Multi-Rate Detection for Frequency Selective Rayleigh Fading CDMA Channels," in *GLOBECOM*, 1998.

[41] I. Oppermann, "Capacity of a DS-CDMA System Supporting Mixed Modulation," in *GLOBECOM*, 1998.

[42] A. Johansson and A. Svensson, "Multistage Interference Cancellation with Decision Directed Channel Estimation in Multirate DS/CDMA on a Mobile Radio Channel," in *PIMRC*, 1998.

[43] P. Kumar and J. Holtzman, "Power Control for a Spread Spectrum System with Multiuser Receivers," Tech. Rep., WINLAB, Rutgers University, 1995.

[44] S. Ulukus and R. D. Yates, "Adaptive Power Control and MMSE Interference Suppression," *Wireless Networks*, 1998.

[45] D. Tse and S. Hanly, "Multiuser Demodulation: Effective Interference, Effective Bandwidth and Capacity," in *Proceedings of Allerton Conference*, Oct. 1997.

[46] D. Tse and S. Hanly, "Effective Bandwidths in Wireless Networks with Multiuser Receivers," in *Proceedings of Infocom conference*, 1998.

[47] D. Tse and S. Hanly, "Linear Multiuser Receivers: Effective Interference, Effective Bandwidth and Capacity," *Submitted to IEEE Trans. on Information Theory*, 1998.

[48] S. Hanly and D. Tse, "Power Control and Capacity of Spread-Spectrum Wireless Networks," *submitted to Automatica, invited paper for special issue*, July 1998.

[49] D. Tse and S. Hanly, "Network Capacity, Power Control, and Effective Bandwidth," in *Wireless Communications: Signal Processing Perspectives*, p. 211. Prentice Hall, 1998.

[50] P. Viswanath, V. Anantharam, and D. Tse, "Optimal Sequences, Power Control and Capacity of Spread-spectrum Systems with Multiuser Receivers," *IEEE Trans. Info. Theory (submitted)*, 1998.

[51] Yile Guo and Behnaam Aazhang, "Capacity of Multirate CDMA System with Multiuser Receiver," *To be submitted to IEEE Trans. Comm.*, 1998.

[52] Yile Guo and Behnaam Aazhang, "Capacity of Multi-class Traffic CDMA System with Multiuser Receiver," *Submitted to WCNC'99*, 1999.

[53] T. Ottosson, *Coding, Modulation and Multiuser Decoding for DS-CDMA Systems*, Ph.D. thesis, Chalmers Univerisity of Technology, 1997.

[54] J. G. Proakis, *Digital Communications*, McGraw-Hill, 1995.

[55] A. J. Paulraj and B. Papadias, "Space-Time Processing for Wireless Communications," *IEEE Signal Processing Magazine*, Nov. 1997.

[56] A. J. Paulraj, C. B. Papadias, V. U. Reddy, and A. Veen, "Blind Space-Time Signal Processing," in *Wireless Communications: Signal Processing Perspectives*, p. 179. Prentice Hall, 1998.

[57] *IEEE Personal Communications, special issue in Smart Antennas*, Feb. 1998.

[58] S.Y. Miller and S.C. Schwartz, "Integrated Spatial-Temporal Detectors for Asynchronous Gaussian Multiple-Access Channels," *IEEE Trans. Commun.*, vol. 43, no. 2/3/4, pp. 396, 1995.

[59] J.H. Winters, J. Salz, and R.D. Gitlin, "The Impact of Antenna Diversity on the Capacity of Wireless Communication Systems," *IEEE Trans. Commun.*, vol. 42, no. 2/3/4, pp. 1740, 1994.

[60] J. V.-Traveset, G. Caire, E. Biglieri, and G. Taricco, "Impact of Diversity Reception on Fading Channels with Coded Modulation — Part I: Coherent Detection," *IEEE Trans. Commun*, vol. 45, no. 5, pp. 563, May 1997.

[61] A. Shah and A. Haimovich, "Performance Analysis of Optimum Combining in Wireless Communications with Rayleigh Fading and Cochannel Interference," *IEEE Trans. Comm.*, vol. 46, no. 4, pp. 473, 1998.

[62] S. Grant and J. Cavers, "Performance Enhancement Through Joint Detection of Cochannel Signals Using Diversity Arrays," *IEEE Trans. Comm.*, vol. 46, no. 8, pp. 1038, 1998.

[63] R. K. Madyastha, *Antenna Arrays for Wireless CDMA Communication Systems*, Ph.D. thesis, Rice University, 1997.

[64] A.F. Naguib, A. Paulraj, and T. Kailath, "Capacity Improvement with Base-Station Antenna Arrays in Cellular CDMA," *IEEE Trans. Vehicular Techno.*, vol. 43, no. 3, pp. 691, Aug. 1994.

[65] J.S. Thompson, P.M. Grant, and B. Mulgrew, "Smart Antenna Arrays for CDMA Systems," *IEEE Personal Communications*, Oct. 1996.

[66] M. Nagatsuka and R. Kohno, "A Spatially and Temporally Optimal Multi-User Receiver Using an Array Antenna for DS/CDMA," *IEICE Trans. Commun.*, vol. E78-B, no. 11, pp. 1489, Nov. 1995.

[67] S. Affes and P. Mermelstein, "Signal Processing Improvements for Smart Antenna Signals in IS-95 CDMA," in *GLOBECOM*, 1998.

[68] A. Morimoto et al, "Problems of Implementing Adaptive Array Antennas in CDMA Systems," in *GLOBECOM*, 1998.

[69] M. Weckerle et al, "The Benefits of Intelligent Antenna Arrays in TD-CDMA - A Study Based on Measured Channel Impulse Responses," in *GLOBECOM*, 1998.

[70] C. Sweatman et al, "Multiuser Detection for CDMA Antenna Array Receivers," in *GLOBECOM*, 1998.

[71] V. Pham and T. Vu, "Adaptive Space-time Full- and Reduced-length MMSE Receivers in Asynchronous DS/CDMA," in *GLOBECOM*, 1998.

[72] J. Lee and J. Byun, "Multiuser Detection using Space-Time Processing in DS-CDMA Systems," in *GLOBECOM*, 1998.

[73] H. Huang and C. Papadias, "Minimum Mean-Squared Error Space-Time Multiuser Receivers for Wireless CDMA Systems," in *GLOBECOM*, 1998.

[74] H. Huang and C. Papadias, "Linear Space-Time Multiuser Receivers for Wireless CDMA Systems," in *PIMRC*, 1998.

[75] F. Rashid-Farrokhi, L. Tassiulas, and K. Liu, "Joint Optimal Power Control and Beamforming in Wireless Networks Using Antenna Arrays," *IEEE Trans. Comm.*, vol. 46, no. 10, pp. 1313, 1998.

[76] F. Rashid-Farrokhi, L. Tassiulas, and K. Liu, "Joint Power Control and Beamforming for Capacity Improvement in Wireless Networks with Antenna Arrays," in *GLOBECOM*, 1996.

[77] F. Rashid-Farrokhi and L. Tassiulas, "Power Control and Space-Time Diversity for CDMA Systems," in *GLOBECOM*, 1998.

[78] Yile Guo and Behnaam Aazhang, "Capacity of Wireless CDMA System using Antenna Array Multiuser Receiver," *To be submitted to IEEE Trans. Comm.*, 1999.

[79] Harri Holma, Antti Toskala, and Tero Ojanpera, "Cellular Coverage Analysis of Wideband MUD-CDMA System," in *PIMRC*, 1997, p. 549.

[80] M. Andersin, Z. Rosberg, and J. Zander, "Soft and Safe Admission Control in Cellular Networks," *IEEE/ACM Trans. Networking*, vol. 5, no. 2, pp. 255, 1997.

[81] Zhao Liu and Magda El Zarki, "SIR-Based Call Admission Control for DS-CDMA Cellular Systems," *IEEE J. Select. Areas. Commun.*, vol. 12, no. 4, pp. 638, 1994.

[82] Zbigniew Dziong, Ming Jia, and Paul Mermelstein, "Adaptive Traffic Admission for Integrated Services in CDMA Wireless-Access Networks," *IEEE J. Select. Areas. Commun.*, vol. 14, no. 9, pp. 1737, 1996.

[83] Yoshihiro Ishikawa and Narumi Umeda, "Capacity Design and Performance of Call Admission Control in Cellular CDMA Systems," *IEEE J. Select. Areas. Commun.*, vol. 15, no. 8, pp. 1627, 1997.

[84] W. Yang and E. Geraniotis, "Admission Policies for Integrated Voice and Data Traffic in CDMA Packet Radio Networks," *IEEE J. Select. Areas. Commun.*, vol. 12, no. 4, pp. 654, 1994.

[85] C. Chao and W. Chen, "Connection Admission Control for Mobile Multiple-Class Personal Communications Networks," *IEEE J. Select. Areas. Commun.*, vol. 15, no. 8, pp. 1618, 1997.

[86] D. Levine and I. Akyildiz, "A Resource Estimation and Call Admission Algorithm for Wireless Multimedia Networks Using the Shadow Cluster Concept," *IEEE/ACM Trans. Networking*, vol. 5, no. 1, pp. 1, 1997.

[87] O. Yu and V. Leung, "Adaptive Resource Allocation for Prioritized Call Admission over an ATM-Based Wireless PCN," *IEEE J. Select. Areas. Commun.*, vol. 15, no. 7, pp. 1208, 1997.

[88] J. Chuang and N. Sollenberger, "Spectrum Resource Allocation for Wireless Packet Access with Application to Advanced Cellular Internet Service," *IEEE J. Select. Areas. Commun.*, vol. 16, no. 6, pp. 820, 1998.

[89] C. Oliveira, J. Kim, and T. Suda, “An Adaptive Bandwidth Reservation Scheme for High-Speed Multimedia Wireless Networks,” *IEEE J. Select. Areas. Commun.*, vol. 16, no. 6, pp. 858, 1998.

[90] G. Anastasi, D. Grillo, and L. Lenzini, “An Access Protocol for Speech/Data/Video Integration in TDMA-Based Advanced Mobile Systems,” *IEEE J. Select. Areas. Commun.*, vol. 15, no. 8, pp. 1498, 1997.

[91] C. Chang, K. Chen, M. You, and J. Chang, “Guaranteed Quality-of-Service Wireless Access to ATM Networks,” *IEEE J. Select. Areas. Commun.*, vol. 15, no. 1, pp. 106, 1997.

[92] A. Sampath and J. Holtzman, “Access Control of Data in Integrated Voice/Data CDMA Systems: Benefits and Tradeoffs,” *IEEE J. Select. Areas. Commun.*, vol. 15, no. 8, pp. 1511, 1997.

[93] J. Wu and R. Kohno, “A Wireless Multimedia CDMA System Based on Transmission Power Control,” *IEEE J. Select. Areas. Commun.*, vol. 14, no. 4, pp. 683, 1996.

[94] J. Wu and R. Kohno, “Performance Evaluation of Wireless Multimedia CDMA Networks Using Adaptive Transmission Control,” *IEEE J. Select. Areas. Commun.*, vol. 14, no. 9, pp. 1688, 1996.

[95] N. Guo, S. Morgera, and P. Mermelstein, “Common Packet Data Channel (CPDC) for Integrated Wireless DS-CDMA Networks,” *IEEE J. Select. Areas. Commun.*, vol. 14, no. 4, pp. 735, 1996.

[96] T. Liu and J. Silvester, "Joint Admission/Congestion Control for Wireless CDMA Systems Supporting Integrated Services," *IEEE J. Select. Areas. Commun.*, vol. 16, no. 6, pp. 845, 1998.

[97] S. Glisic and J. Vikstedt, "Effect of Wireless Link Characteristics on Packet-Level QoS in CDMA/CSMA Networks," *IEEE J. Select. Areas. Commun.*, vol. 16, no. 6, pp. 875, 1998.

[98] S. Oh and K. Wasserman, "Dynamic Spreading Gain Control in Multi-Service CDMA Networks," *IEEE J. Select. Areas. Commun. (to appear)*, 1998.

[99] S. Choi and K. Shin, "Uplink CDMA Systems with Diverse QoS Guarantees for Heterogeneous Traffic," in *ACM/IEEE MobiCom*, 1997.

[100] K. Park and D. Cho, "Providing Variable-Rate Transmission for the Integrated Multimedia Services in the CDMA Network," in *GLOBECOM*, 1998.

[101] J. Laakso et al, "Radio Resource Knapsack Packing for WCDMA Air Interface," in *GLOBECOM*, 1998.

[102] M. Arad and A. Leon-Garcia, "A Generalized Processor Sharing Approach to Time Scheduling in Hybrid CDMA/TDMA," Tech. Rep., University of Toronto, 1997.

[103] V. Veeravalli and B. Aazhang, "On the Coding-Spreading Tradeoff in CDMA Systems," in *Proc. 1996 Conf. Inform. Sci. Syst.*, March 1996.