Radio Resource Management in Cellular CDMA Systems Supporting Heterogeneous Services

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

A novel radio resource management (RRM) scheme, which jointly considers the system characteristics from the physical, link and network layers, is proposed for cellular code division multiple access (CDMA) systems. Specifically, the power distribution at the physical layer distributes only the necessary amount of power to each connection in order to achieve its required signal-to-interference-plus-noise ratio (SINR). The rate allocation guarantees the required delay/jitter for real-time traffic and the minimum transmission rate requirement for non-real-time traffic. Efficient rate allocation is achieved by making use of the randomness and burstiness of the packet generation process. At the link layer, a packet scheduling scheme is developed based on the information of power distribution and rate allocation from the physical layer to achieve guaranteed quality of service (QoS). It schedules the system resource on a time slot basis to efficiently utilize the system resource in every time slot and to improve the packet throughput for non-real-time traffic. A connection admission control (CAC) scheme based on the lower layer resource allocation information is proposed at the network layer. The CAC scheme also makes use of user mobility information to reduce handoff connection dropping probability (HCDP). Theoretical analysis of the grade of service (GOS) performance, in terms of new connection blocking probability (NCBP), HCDP, and resource utilization, is given. Numerical results show that the proposed RRM scheme can achieve both effective QoS guarantee and efficient resource utilization.

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List of Abbreviations

bps	bit per second
cps	chip per second
i.i.d.	independent identically distributed
pdf	probability density function
r.v.	random variable
ABR	available bit rate
ARQ	automatic repeat request
ATM	asynchronous transfer mode
AWGN	additive white Gaussian noise
BPSK	binary phase shift keying
BS	base station
BER	bit error rate
CAC	connection admission control
CBR	constant bit rate
CDMA	code division multiple access
DS-CDMA	direct sequence code division multiple access
FCFS	first-come-first-served
FCTP	forced connection termination probability

FDD	frequency division duplexing
HCDP	handoff connection dropping probability
MAC	medium access control
MAI	multiple access interference
MC-CDMA	multi-code code division multiple access
MS	mobile station
MSC	mobile switching center
NCBP	new connection blocking probability
PIF	power increase factor
PSD	power spectrum density
QoS	quality of service
RRM	radio resource management
RS	Reed-Solomon
RTT	ready-to-transmit
SINR	signal-to-interference-plus-noise ratio
SIR	signal-to-interference ratio
TDD	time division duplexing
TDMA	time division multiple access
UBR	unspecified bit rate
VBR	variable bit rate

Nomenclature

α	path loss attenuation factor
η	activity factor of ON-OFF source
γ_i	actual SINR at the BS receiver input for ith class connection
γ_i^*	minimum required SINR for ith class connection
λ_i	average connection arrival rate of ith class connections
λ_i^h	average handoff connection arrival rate for ith class connections
$\mathbf{k}^{\mathrm{a}}$	admissible state, $\mathbf{k}^{\mathrm{a}} = (k_1^{\mathrm{a}}, k_2^{\mathrm{a}}, \ldots, k_K^{\mathrm{a}})$
μ_i	average service rate of ith class connections
ν_i	inversion of average inter-handoff time of mobiles carrying ith class connections
ϕ_i	resource reservation coefficient for ith traffic class
$\pi(\mathbf{k}^{\mathrm{a}})$	equilibrium probability of state $\mathbf{k}^a$
ρ_i	packet generation rate for ith class CBR connection; average packet generation rate for ith class VBR connection; minimum transmission rate for ith class ABR connection

σ_i	maximum packet burstiness for ith class (VBR) connection
τ	time interval for updating mobility information
ϱ_i	average net ith class traffic to a cell
A_i	packet generation rate of ON-OFF source in ON state
a_i	transition probability from ON state to OFF state for ON-OFF source
B_{b}	baseband bandwidth
B_i	buffer size allocated to ith class connection
b_i	transition probability from OFF state to ON state for ON-OFF source
C_i	resource utilization of ith traffic class
D_i	maximum delay tolerance for ith class (CBR or VBR) connection
d_j	distance between BS and mobile carrying jth connection
f	ratio of inter-cell MAI to intra-cell MAI
G	spread spectrum processing gain
K	total number of traffic classes
K^{a}	number of ABR traffic classes
K^{c}	number of CBR traffic classes
K^{v}	number of VBR traffic classes
k_i	number of connections in ith traffic class

$m_j R_{\mathrm{b}}$ allocated transmission rate for jth connection

N_0 one-sided PSD of background AWGN

p_i^{w} BER due to wireless transmission for ith class connection

p_{bou} handoff probability of mobile u from cell b to cell o

p_i^{b} BER due to buffer overflow for ith class connection

P_i^{h} HCDP for ith class connections

P_i^{n} NCBP for ith class connections

P_j^{m} maximum transmission power for mobile carrying jth connection

P_j^{t} required transmission power for mobile carrying jth connection

R_{b} basic MC-CDMA packet transmission rate

S_j receive power for jth connection under perfect power control

$S_j^{'}$ receive power for jth connection under imperfect power control

T^{f} channel frame length

V_i effective transmission rate for ith class (VBR) connection

W spread spectrum bandwidth

Chapter 1

Introduction

1.1 Evolution of wireless communication networks

The growth of mobile communications is explosive. Now wireless mobile communications have developed from the first and second generation systems to the third generation systems. Evolution toward fourth generation wireless communications standards is underway. Table 1.1 shows the evolution trend. The first generation (1G) wireless mobile communication systems were developed in 1980s. They used frequency modulation (FM) for voice communications and frequency division multiple access (FDMA) as the access technique. Examples of such systems were advanced mobile phone service (AMPS) in United States, Total Access Communication System (TACS) in Europe, and NTT in Japan. The user capacity of the 1G technologies was heading towards saturation caused by the rapid growth of demands for mobile communications.

The second generation (2G) systems, introduced to the market around 1991, offer better voice quality and more efficient spectrum utilization. The new systems utilize digital modulation techniques. Presently, the 2G systems are GSM, TDMA IS-136, PDC and cdmaOne. Besides voice services, the second generation systems can also provide short messages and low-rate data services at rates of 9.6-14.4 kbps. Both 1G and 2G systems are circuit-switched, which is not efficient, especially in handling packet-oriented services.

The primary objectives for the third generation (3G) systems focus on universality, high data rate, flexibility, service quality and service richness. The data transmission is at least 144 kbps in vehicular, 384 kbps in outdoor-to-indoor (wide area), and up to 2 Mbps in indoor and picocell environments (local area). 3G systems allow both circuit switching and packet switching and open the possibility to provide advanced and flexible quality of service (QoS) support. Delay sensitive services, such as voice and video, can be served in circuit-switched mode, while data traffic, which can tolerate relatively long delay, can be served in packet-switched mode to efficiently utilize the system resource. The shift to 3G in the radio access networks is presently ongoing. Code division multiple access (CDMA) is the selected approach for 3G systems. Wideband CDMA (W-CDMA), using direct-sequence code division multiple access (DS-CDMA) as access technology, has been proposed by the European community as the 3G wireless standard [1]-[5]. cdma2000, using multi-carrier CDMA as access technology, is the counterpart proposal by the United States. Evolution from 2G to 3G systems is not completed in one step. An important evolution step is the so-called 2.5G systems. The General Packet Radio Service (GPRS) is an evolved GSM system with packet-switched solutions. The shift from cdmaOne to cdma2000 goes through cdma2000 1x and cdma2000 3x. The divergence between standards limits the roaming of users between different networks.

Research on fourth generation (4G) mobile communication systems is already underway. Internet protocol (IP) can potentially become the universal network-layer protocol over all wireless systems as it already is for wireline packet networks [6]-[9]. Currently, the 4G research is mainly on 1) to provide higher data rate, 2) to achieve global roaming and horizontal communications between different access technologies, and 3) to provide a common platform which can provide more advanced types of services.

Mobility was the igniting idea for the development of 1G mobile communications. However, multiple incompatible standards in 1G prohibited the user roaming among different networks. Since then, user mobility has been developed from "terminal mobility" to "personal mobility". When a single application (e.g., voice) is supported, such as in 1G systems, mobility can be resolved by a single terminal. While in GSM systems, mobility is centralized around the person who uses the terminal for one or more applications, since the user can access any service by any network-compatible terminal. This type of personal mobility will be well supported in 3G systems and will be supported even more in 4G systems by introducing interworking units that provide seamless roaming between networks of different standards without any interruption.

In general, the rapid evolution of wireless mobile communications has been driven by i) the high demand of wireless communications and mobility, ii) the requirements of high quality applications, iii) the need of new applications, and iv) the technical development. In the future, mobile users expect to enjoy the same set of services and high QoS that are seamless in both fixed and mobile environments. Future wireless systems are required to provide greater mobility and adequate QoS support as a user moves from place to place. In addition, future applications will demand more resource than ever. Therefore, resource management will play a vital role in future wireless communication systems in delivering a target QoS and optimizing network resource utilization.

Table 1.1: Evolution of wireless communications

	2G	2.5G	3G	3G+
Air interface	TDMA CDMA	TDMA CDMA	CDMA	CDMA
Major systems	GSM cdmaOne	GPRS cdma2000 1x	WCDMA cdma2000	WCDMA cdma2000
Switching mode	circuit-switched	packet-switched	packet-switched	packet-switched
Applications	voice mainly+ low-rate data	voice and data	multimedia	multimedia virtual reality
Data rate	9.6-14.4 kb/s	64-144 kb/s	384 k b/s-2 Mb/s	10-100 Mb/s

1.2 Radio resource management and challenging issues

Future wireless communication networks will support heterogeneous services with different characteristics and QoS requirements, such as packet delay/jitter requirements, bit error rate (BER), and signal-to-interference-plus-noise ratio (SINR). Radio resource management (RRM) plays a vital role in wireless communications systems to efficiently utilize the limited radio resources while guaranteeing the required QoS performance for mobile users. In a wide sense, RRM in wireless communication systems includes two aspects:

(1) How to design a network infrastructure such that the system capacity is maxi-

mized? This includes waveform design, base stations (BSs) and antenna deployment, modulation and coding schemes, etc.

(2) Given a certain infrastructure design, how should the wireless resources be allocated to meet the QoS requirements of the mobile users while accommodating more mobile users in the network?

The first aspect has been studied extensively, e.g., [13] and [14]. The RRM research in this thesis is based on a given network infrastructure and therefore emphasizes on the second aspect. The aim of the RRM is (1) to provide guaranteed QoS for heterogeneous services, and (2) to efficiently utilize the precious radio resource. While the cellular CDMA network offers a lot of advantages, such as high capacity, high spectrum utilization and user mobility, it also brings a lot of challenging issues when supporting heterogeneous services.

1.2.1 Heterogeneous services

Future wireless cellular communication networks are expected to support heterogeneous traffic with a wide range of transmission rates, BER requirements, and delay/jitter requirements. For example, voice and video are real-time traffic and cannot tolerate long delay; while most data traffic can tolerate large delay, they are very sensitive to transmission errors. Different amounts of resource should be allocated to different types of traffic in order to satisfy their unique QoS requirements. Services requiring higher QoS require more system resources. Since QoS corresponds to the system capacity, heterogeneous services make the system capacity study a complex issue. In CDMA, the resource sharing property opens the opportunity to flexibly multiplex different traffic and the available resource, and the potential of efficient resource utilization. How to coordinate the different QoS requirements for different types of traffic coexisting in the same system is a very challenging problem. Therefore, effectiveness is the first problem to be solved by the RRM in this research.

1.2.2 Limited radio resource

The available radio frequency bands are limited due to technical limitation. The usage of the available radio frequency bands is also regulated and coordinated by special organizations. Unlike wireline network resource, which can be added simply by adding more devices, the available radio resource in wireless network is very limited and precious. Radio transmission experiences path loss and is range-limited. Since signals are transmitted in open space, transmissions from different users at the same time interfere with each other if they are at the same frequency bands. Higher transmission power from one user increases the interference to other users. Too much interference reduces the SINR and increases the BER. Therefore, wireless systems are also power limited or interference limited, and the radio resource should be utilized efficiently. For a given amount of bandwidth, an efficient RRM should: 1) admit into the system as many connections as possible, and 2) achieve high packet throughput for the admitted connections. The efficiency is achieved subject to the effectiveness. In practice, however, the system resources can never be fully utilized due to intolerably high connection blocking probability.

1.2.3 User mobility

User mobility in wireless cellular networks is another important factor that needs to be dealt with by the RRM. A mobile user usually moves randomly in the system.

In a cellular system, as the user moves away from the BS, the required transmission power from the mobile station (MS) increases in order to achieve the same QoS at the BS receiver end. When a user moves close to the boundary of the cell, the required transmission power may exceed the MS's maximum transmission power and result in communication outage. Therefore, RRM in a cellular network should take mobile users' movement into consideration and ensure that the required QoS can be guaranteed throughout the connection's lifetime while the mobile is moving.

As a mobile user moves across a cell boundary, its connection should be handed off from its previous cell to the new cell. Connection dropping may happen if the new cell does not have enough resource to accept the connection. As the cell size of a cellular network becomes small, an active connection may handoff several times during its entire lifetime. Frequent handoffs may result in high connection dropping probability, especially when the system is in high traffic load. Due to random handoffs, the number of active users are random in each cell so is the available resource in each cell.

1.2.4 Hostile radio channel

Wireless transmission medium is a hostile radio channel. The MS movement in cellular networks further causes the radio link quality to be highly erratic. Besides large scale attenuation due to path loss, wireless transmission experiences slow fading due to shadowing, and fast fading due to reflection of buildings or other blockage. Slow fading results in variation of the local mean power, and fast fading results in fast variation of the signal strength over a short distance. Since the physical transmission quality directly impacts on the success of the packet transmissions and therefore the QoS of the connections in the system, it should be taken into account in the RRM research.

Channel fading causes high rate of transmission errors in the radio channel. Power control is one way to mitigate the slow fading due to shadowing, and a RAKE receiver or multi-user detector can be used to overcome the fast fading. Besides, channel coding/decoding and interleaving/deinterleaving may be used to improve the BER vs. SINR performance. Channel fading increases the required system resource to achieve the same QoS and reduces the system capacity.

The ability of radio links to withstand interference, and that of the cellular system to react to variations in the traffic and user movement are the main factors in determining the spectral efficiency of the cellular systems. Hence, for cellular heterogeneous systems, effective and efficient RRM is necessary.

1.3 Background and related work on RRM

1.3.1 CDMA

Future wireless communication networks will likely be CDMA-based. A CDMA system uses two-stage modulation, regular data modulation and spread spectrum modulation. Spread spectrum [10]-[11] was originally developed for military applications to provide antijam and low probability of intercept communications by spreading a signal over a large frequency band and transmitting it with a low power per unit bandwidth. Spread spectrum signals have the distinguishing characteristic that the bandwidth used is much greater than the message bandwidth. This band spread is achieved by using a spreading code or pseudonoise (PN) sequence that is independent of the message and is known to the receiver. The receiver uses a synchronized replica of the PN sequence to despread the received signal allowing recovery of the message. When spectrum spreading is performed by phase modulation, the resultant signal is called direct-sequence (DS) spread spectrum, and the corresponding CDMA system is a DS-CDMA system. While it appears that any cellular system can be suitably optimized to yield a competitive spectral efficiency regardless of the multiple access technique being used, CDMA offers a number of advantages. The advantages of CDMA for cellular applications include i) universal one-cell frequency reuse: because all cells can use all carrier frequencies, the frequency reuse plan is greatly simplified, and the spectrum utilization is significantly improved, ii) inherent multipath diversity in DS-CDMA: because the transmission bandwidth is much higher than the signal bandwidth, multipath signals can be resolved in time which results in increased diversity, and iii) ability to exploit silent periods in speech voice activity: by making use of the silent periods when less powers are transmitted, system capacity can be improved. Besides, DS-CDMA also has some salient properties, such as the ease of implementing soft-handoff, soft capacity and narrow band interference rejection. Because of the inherent immunity to noise, interference, and channel fading, much higher system capacity can be achieved in CDMA systems than that in FDMA and TDMA systems.

1.3.2 Capacity and utilization analysis

For a single cell CDMA system, suppose all users have the same traffic to transmit, and each user's transmitted power is perfectly controlled so that all signals are received at the BS at equal power levels. If the received signal power of each user is S, and the background noise is additive white Gaussian noise, the following inequality holds for the uplink:

$$\frac{S}{(N_{\mathrm{u}}-1)S+N_0W}\frac{W}{R_{\mathrm{b}}}\geq\gamma^* \tag{1.1}$$

where N_0 is the one-sided power spectral density (PSD) of the background noise, W is the spread spectrum bandwidth, R_b is the signal bandwidth before spread spectrum modulation, γ^* is the required SINR ratio, and N_u is the number of total supportable users. The maximum value of N_u is the uplink capacity.

Practical capacity analysis for CDMA systems has been a challenging issue, especially in the presence of channel fading, imperfect power control, user movement and heterogeneous services. Capacity analysis for homogeneous traffic is studied in [15]-[17], that for integrated voice and data traffic is studied in [18]-[19], and for heterogeneous traffic is studied in [20]-[21]. Capacity increase through sectorization and voice activity monitoring is studied in [15]. It is shown in [16]-[17] and [19] that user mobility can remarkably affect the cellular CDMA system capacity. The cellular CDMA system in [20] supports multi-class traffic with each having different transmission rate and SINR requirements. The capacity analysis in [15] is based on a slow fading channel, and that in [21] is based on a fast fading channel. Capacity of CDMA systems with matched filter receivers in fading channels is studied in [22]. Capacity analysis for a variable spreading gain CDMA system supporting two class services with different rate and QoS requirements is studied in [23]. Other capacity analysis can be found in [24]-[27].

Much work has been done to improve the system capacity in different ways. CDMA is interference limited. Reduction in interference is equivalent to increasing system capacity. Any approach that can reduce the required SINR, γ^*, for given BER requirement, or that can reduce the MAI, improves the system capacity. A system with channel coding and decoding may improve the system capacity [28]. The waveform of CDMA signals facilitates utilization of multipath diversity. A benefit is obtained when the resolved multipath signals are combined using RAKE receiver [29] if the signals arrive more than one chip apart from each other. Multiuser detection [30], also called joint detection and interference cancelation, provides means of reducing the effect of MAI, and hence increases the system capacity.

No practical system can utilize all the system capacity due to intolerably high connection blocking probability. Erlang capacity is defined as the average traffic load in terms of the average number of users requesting services resulting in a predefined connection blocking probability. Erlang capacity for a cellular CDMA system is studied in [31] for voice only traffic, in [32] for integrated voice and data traffic, and in [33] for heterogeneous traffic. The Erlang capacity for given blocking probability is approximately analyzed in [31] taking into consideration of imperfect power control, activity factors, and different QoS requirements. A system supporting multiple traffic classes is modeled as a multi-dimension M/M/m Erlang loss system in [33].

1.3.3 Power control

Power control is a basic system requirement for CDMA. Originally, power control was proposed for a CDMA system to overcome the near-far problem so that the received power for all the (homogeneous) connections are the same in order to achieve the same QoS. In CDMA systems with heterogeneous traffic, power control could also be used to achieve a target power for each connection in order to limit the MAI interference to other users and to achieve its required SINR.

In 3G W-CDMA and cdma2000 systems, the reverse link power control includes the open loop power control and the closed loop power control. The open loop power control is based on the principle that a mobile closer to the BS needs to transmit less power as compared with a mobile that is far away from the BS. The mobile adjusts its transmit power based on the received power level from the BS. If the received power is high, the mobile reduces its transmit power. Otherwise, the mobile increases its transmit power. The BS is not involved in this process. The reverse link closed loop power control consists of two parts: the reverse inner loop power control and the reverse outer loop power control. The inner loop power control keeps the mobile as close to its target signal-to-interference ratio (SIR) as possible (noise is neglected compared with interference), and the outer loop power control adjusts the target SIR for a given mobile. The target SIR may vary with vehicle speed and RF environment. The relatively fast variations associated with Rayleigh fading may at times be too rapid to be tracked by the closed-loop power control, but variations in relative path losses and shadowing effects is generally slow enough to be controlled. Also, while Rayleigh fading may not be the same for forward and reverse links, log-normal shadowing normally will exhibit reciprocity. Details about how to implement power control for CDMA systems are discussed in [34]-[39].

Ideally, if perfect power control can be achieved, the required SINR for each user can be guaranteed by accurately distributing the received power for all the users, as long as the traffic load is within the system capacity. In reality, however, due to channel estimation errors, power control delay, power control command transmission errors, etc., imperfection in power control always exists. Due to the randomness of power control errors, it is unlikely to achieve the target SINR exactly at the receiver end and communication outage occurs occasionally. The outage probability is defined as the probability that the actual received SINR is below the minimum required SINR of a connection. Capacity of CDMA systems under imperfect power control has been analyzed in [24] and [25] for homogeneous voice traffic. The effect of power control imperfection on the throughput and delay of data traffic has also been studied in [24].

In [25], capacity of a cellular CDMA system for homogeneous services is estimated taking into consideration of imperfect power control, user distribution, and channel fading. BER performance and link availability have been derived for homogeneous CDMA systems with imperfect power control in [40] and [26], respectively. The effect of power control and its imperfection on the forward-link capacity in cellular CDMA systems is studied in [27]. Erlang capacity for a cellular CDMA voice system has been studied in [31] for given connection blocking probability, where the Erlang capacity is derived as a function of the Erlangs per cell, intercell to intracell interference ratio, and power control standard deviation.

1.3.4 Power distribution

Power as the common resource makes CDMA very flexible in handling mixed services. By allocating a different amount of power to each user according to its unique traffic parameters and QoS requirements, multiplexing of services with very different characteristics can be achieved in an efficient way. Much work has been performed in the area of designing QoS-based power distribution algorithm for finding the minimum power or maximizing the system capacity for given SINR required by users.

It is shown in [41] that, equal receive powers for homogeneous service is optimal in a uniformly loaded CDMA system to maximize system resource utilization. The idea of assigning different transmitted powers to achieve different QoS levels in DS-CDMA is proposed in [42]. Power distribution for two traffic classes with perfect power control is studied in [43], where each class requires different transmission rates and SINRs, and the system outage probability is derived based on a two-dimensional Markov chain model. Power distribution for data traffic only and for integrated voice and data traffic is studied in [44], where different transmission rates are supported by variable processing gain. Power distribution for integrated voice and video traffic is discussed in [45] with perfect power control. The effect of equal power distribution to different types of traffic is studied. Power distribution and resource management is studied in [46] as an optimization problem to minimize the total interference or to maximize the transmission throughput. An optimal power control law is derived in [47] for multi-rate multimedia traffic to maximize the system resource utilization or minimize power consumption. The analysis is based on an asynchronous DS-CDMA system and takes both fast and slow fading into consideration. Dynamic programming is used to solve the problem. Power distribution for non-real-time services in downlink channels is studied in [48]. The power distribution algorithm provides guaranteed average data transmission rate with minimum energy consumption by using intra-cell scheduling. Other power distribution schemes for multi-rate services can be found in [49]-[50]. Practically all of the power distribution works assume the existence of an optimal solution and study the behavior of the proposed power control algorithm when it does converge to the solution. The existence of a solution for any power control or power distribution law is proved in [51] to be a function of the spread bandwidth, user data rates, and user QoS specifications. A power distribution algorithm and a rate allocation strategy are proposed for multi-rate CDMA systems in [51].

1.3.5 Rate allocation

Provision of a large variety of transmission rates may be implemented in two ways: allocating each user one code channel that has a variable spreading gain [23], or allocating multiple codes to each user so that the individual user data streams are split into parallel lower rate streams which in turn are each spread by different orthogonal codes. A combination of the two is also feasible. Investigation of the effects of these configurations on the overall system performance is studied in [55]. The effect of dynamic spreading gain control on the CDMA system performance is studied in [56]. A dynamic rate allocation scheme is proposed in [57] to maximize the system transmission throughput while guaranteeing the required QoS performance. SIR and rate allocation for CDMA data users on the forward link is studied in [59]. The SIR and rate allocation is subject to required delay and error performance and average and peak power constraints. A joint rate and power allocation problem is proposed and solved in [58] to maximize the throughput of non-real-time traffic and to ensure the required QoS performance of real-time traffic, where the multi-rate is supported by variable processing gain. In [60], a similar optimization problem for joint rate and power control is solved by using geometric programming.

1.3.6 MAC and packet scheduling

A MAC protocol regulates how different connections share and compete the available system resource. A MAC protocol can be fixed or dynamic. In a fixed MAC protocol, each connection in the system is allocated a fixed amount of resource. Fixed MAC protocols are easy to implement, but usually result in waste of system resource for random arriving packets. Therefore, dynamic MAC protocols are adopted to multiplex the traffic randomness in order to more efficiently utilize the system resource. The dynamic MAC protocols can be further divided into random access schemes and reservation-based schemes. A packet scheduling scheme in the MAC protocol coordinates the packet transmissions from different connections such that: i) the required packet delay/jitter and loss requirements of different connections can be guaranteed, and ii) high packet throughput can be achieved.

A random access MAC protocol (and packet scheduling scheme) is proposed in [61] to support heterogeneous traffic in hybrid CDMA and TDMA systems. Each user is assigned a priority level. A user with higher priority is assigned to a higher transmission probability, and therefore experiences a short average delay. Because of the random access, packet transmissions may collide with each other and have to be retransmitted. The MAC protocol cannot guarantee maximum delay requirements, therefore is not suitable for delay sensitive real-time traffic. To reduce the resource waste due to transmission collision, reservation-based MAC protocols are preferred, especially for real-time traffic. In [65], a packet scheduling scheme called WISPER is developed to support multimedia traffic based on a hybrid TDMA and multicode CDMA (MC-CDMA) system. The scheme schedules the transmissions of multimedia packets according to their BER requirements, so that the packets with equal or similar BER requirements are transmitted in the same slots. The WISPER scheme uses complicated iterative procedure to implement. All the mobiles have the same power at the BS receiver input, even though carrying different traffic. The scheduling scheme in [48] is also designed for non-real-time data services. In this scheme, transmission rate for each connection is scheduled to provide a requested average transmission rate, while the power resource is distributed to minimize energy consumption. A MAC protocol for multi-rate traffic is proposed in [62]. It enhances the TDMA-based DQRUMA [53] protocol in multi-code DS-CDMA systems supporting multi-rate transmissions. Transmission power is allocated to each connection based on a Maximum Capacity Criterion while providing satisfied SINR to all connections.

To reduce the request access overhead and ensure the required small delay, real-time traffic, e.g., voice and video, is usually served in a circuit-switched mode. On the other hand, to improve the resource utilization, non-real-time traffic is usually served in a packet-switched mode. Such an example is the packet scheduling scheme in [66]. The MAC protocol proposed in [62] is extended in [63] to incorporate different traffic classes, both real-time and non-real-time traffic. For real-time traffic, connection-oriented transmission is achieved by assigning a set of mobile-oriented code channels and reserving an appropriate bandwidth. Therefore, the delay performance can always be satisfied. Non-real-time traffic is served by the remaining resource from serving real-time traffic through best effort.

Access control for integrated voice and data traffic has been studied extensively [67]-[71] because of the complementary QoS requirements that voice traffic and data traffic have. Voice requires a continuous bit stream service, is intolerant to delays, and can tolerate occasional loss, whereas data is error intolerant, suitable for discontinuous packetized transmission, and tolerant to moderate or long delays.

1.3.7 Connection admission control

The connection admission control (CAC) is to make a decision about whether a new or handoff connection should be admitted into a system according to the current system traffic load and the QoS requirements of the new/handoff connection. The admission decision is critical to both the system and the users, since admitting a connection that should not be admitted results in overload of the system, and the QoS of all the current connections would be deteriorated. On the other hand, rejecting a connection that can be provided with guaranteed QoS would waste the system resources. CAC decision-making should have the following at its disposal: (i) a mechanism to compute the resource usage of ongoing connections and the amount of unallocated resource for allocation, (ii) a mechanism to allocate the available resource to admit new connections,

(iii) a mechanism to enforce control subject to satisfaction of QoS specification, and (iv) provision to admit handoff connections with a higher probability than new connections.

Homogeneous services are considered in [72], where admission of a connection is determined by interference. For a new connection request, if the interference after assigning one more channel and reserving a certain number of channels for handoffs is less than the total interference margin specified by the system, the connection is accepted. This scheme is based on the periodical measurement report of current interference.

An SIR-based CAC algorithm is proposed in [73] for homogeneous traffic. A concept of residual capacity is defined as the additional number of initial connections a BS can accept such that system-wide outage probability could be guaranteed. The BS makes periodical measurement of the SIR and updates the value of residual capacity. If the residual capacity is greater than zero, the system can accept a new connection.

Two different CAC schemes are considered in [74]: number-based CAC (NCAC) and interference-based CAC (ICAC). The NCAC admits a new connection if the total number of existing connections in the system is less than a predefined value, while the ICAC admits a new connection if the total interference in the system is less than a certain threshold. The predefined number of connections supported in the NCAC-based systems and the interference threshold specified in the ICAC-based systems are determined by the connection blocking probability and the communication outage probability. Homogeneous service is supported. There is no distinction of handoff connections from new connections.

In [75], different traffic classes are defined as requiring different number of basic bandwidth units (BBUs). The QoS criteria are system defined connection dropping probability and connection blocking probability. When a new connection arrives, if there are sufficient number of BBUs available in the home cell and the handoff dropping probability requirements in the home and neighbor cells are met, the new connection is admitted into the system. When a handoff connection arrives, two approaches are proposed, completely sharing and partition-based reservation. The former provides good system capacity, but is biased against the traffic classes requiring more BBUs. The latter achieves relatively fair sharing of the resources, but wastes the system resources compared with the former.

An adaptive CAC scheme is proposed in [76] for integrated services wireless-access networks based on CDMA. It estimates mean and variance of the interference based on measurement and source declarations by using a linear Kalman filter. The estimated interference is used to calculate the BERs for each connection in the system. Heterogeneous services with different BER requirements are supported by the CAC scheme. The admission decision is to accept a connection if, after the connection is admitted, the BERs of all the connections do not exceed the required values.

Capacity analysis and CAC scheme for a CDMA system in fading channel is studied in [21]. Heterogeneous services with different transmission rates, delay and BER requirements are considered. The CAC algorithm first finds the maximum acceptable number of homogeneous traffic connections in the system with satisfactory BER and delay requirements. This process statistically multiplexes the traffic randomness and burstiness among the same class connections. The required SINR threshold is also calculated. Based on the SINR calculation and interference measurement, the required transmission powers for all the connections are calculated. A new connection is admitted if there exist converged solutions to the transmission powers.

1.3.8 Handoff

As the cell size becomes small in future cellular networks in order to improve the system capacity, an active connection may be handed off multiple times during its lifetime. When a user requests to hand off from its current cell to a neighboring cell, the new cell may not have enough resources to accept the user's connection. Rejecting a handoff connection is called connection dropping which is undesirable. To reduce the probability of connection dropping, it is better to have some knowledge of user mobility information so that some resources are reserved for potential handoff connections. User mobility information is the probability that a mobile user will reside in a particular cell at future moments, and is determined by the users' movement, including initial location, speed, and direction. Different approaches have been proposed to predict the user mobility information in the future moments from its mobility information of current and previous moments. A fuzzy logic inference system is used in [77] to estimate the user mobility information for a wireless ATM network which uses a DS-CDMA protocol. In [78], a hierarchical user mobility model, together with pattern matching and Kalman filtering techniques is used for location prediction of the mobile users. Effect of user mobility on the performance of cellular CDMA systems is studied in [16] and [80].

Handoff connections should be assigned a higher priority than new connections, because interruption of an on-going connection is much more undesirable than refusing to admit a new connection from the point of view of users. Some resource reservation schemes for TDMA based homogeneous wireless networks have been proposed to allocate part of the network resources for potential handoff connections. The *Guard channel* approach is proposed in [79], where a fixed amount of resource is exclusively reserved for handoff connections. Virtual connection tree (VCT) concept is proposed in [81], which is a group of pre-established connections between a fixed switch and a set of BSs with which the mobile could potentially associate. A mobile can freely handoff to any cell within the VCT without being subject to a new admission control. Homogeneous traffic is considered in [81] to make the admission decision. A shadow cluster concept is proposed in [83]. A shadow cluster is a set of BSs that a mobile may influence in the near future and moves along with the mobile. The shadow cluster concept together with user mobility information is used in the CAC scheme in [83] to predict the resource demand in near future and to reserve resources accordingly. The CAC scheme presented in [84] allocates the required resources for a connection in its current cell and adaptively reserves resources in all the neighboring cells for it. The amount of reserved resources is determined by the QoS requirements of the connection and the current traffic load of the network, and adjusted dynamically. Performance analysis for cellular systems with handoffs is investigated in [96]-[99] for homogeneous services under different resource reservation and user mobility models.

1.4 Research motivation

Research work on RRM has been performed extensively at each layer of the CDMA-based wireless mobile networks. At the physical layer, the RRM studies the relationship among the number of users, SINR, and transmission rate. Research at the physical layer does not consider traffic heterogeneity, link quality, connection blocking and actual resource utilization. Effective and efficient power distribution and rate allocation at the physical layer provide the basis for effective and efficient higher layer resource management. Packet scheduling at the link layer and CAC at the network layer are performed based on the power distribution and rate allocation policies. The packet scheduling is necessary to coordinate the transmission rates and powers of different connections in the system to satisfy the packet level QoS requirements and to achieve high throughput for given number of connections. The number of connections is actually determined by CAC at the network layer. If a CAC scheme cannot admit enough connections, it may be impossible for the packet scheduling scheme to achieve the best packet throughput. Or if a CAC admits too many connections, it may cause network congestion, and the required QoS may not be guaranteed. The CAC makes a decision about whether a connection request can be accepted or not. The admission decision for a connection should be based on the transmission capability of the lower layer. The admission decision is usually made according to current interference level, or number of connections already in the system. The CAC should make an admission decision for a connection such that once admitted, guaranteed QoS can be provided for the connection throughout the connection's life time. Therefore, it should take mobile user's movement into consideration. An effective and efficient CAC should also reserve an appropriate amount of resources for potential handoff connections. Reserving more resources achieves lower HCDP, but reduces the resource utilization and increases the NCBP. In general, different system characteristics at the physical, link and network layers may be correlated. Consideration of the individual layers in isolation can lead to inefficient resource utilization and problems in QoS provisioning.

In this thesis, a novel RRM scheme is proposed by jointly considering the system characteristics from the physical, link and network layers. The objective of the proposed RRM is to efficiently utilize the available system resource while providing more mobile users with guaranteed QoS. Specifically, to allow the maximum number of simultaneously transmitting users, only the necessary amount of power to achieve its required

SINR is distributed to each connection. The rate allocation guarantees the required delay/jitter for real-time traffic and the minimum transmission rate requirements for non-real-time traffic. Efficient rate allocation is achieved by making use of the randomness and burstiness of the packet generation process. At the link layer, a packet scheduling scheme based on the power distribution and rate allocation to achieve guaranteed QoS for heterogeneous traffic is developed. It schedules the system resource on a time slot basis to efficiently utilize the system resource in every time slot and to improve the packet throughput for non-real-time traffic. A CAC scheme based on the lower layer resource allocation information is proposed at the network layer. The CAC scheme also makes use of user mobility information to reserve resources for handoff connections.

1.5 Overview of the thesis

The remainder of this thesis is organized as follow. Chapter 2 defines the system model. Problem formulation of the RRM research is described in Chapter 3. Chapter 4 studies the power distribution under perfect and imperfect power control. Transmission rate allocation to heterogeneous services is presented in Chapter 5. A packet scheduling scheme is developed in Chapter 5 based on the power distribution and rate allocation policies. Chapter 6 proposes the CAC scheme with resource reservation for potential handoff connections. Grade of service (GOS) performance at the connection level, in terms new connection blocking probability (NCBP), handoff connection dropping probability (HCDP), and resource utilization, is also derived in Chapter 6. Numerical results are demonstrated in Chapter 7. Concluding remarks and future research work are listed in Chapter 8.

Chapter 2

System Model

In this chapter, the CDMA system model and the scope of this research are defined.

2.1 Network structure

Wireless cellular communication is the public communication approach to provide high system capacity and user mobility for mobile users. Future wireless communications are expected to support multimedia services. Fig. 2.1 shows a network architecture delivering end-to-end transportation in a hybrid wireless/wireline network. A mobile switching center (MSC) serves as the access point for the wireless network to connect to the wireline backbone network. The wireless segment is called radio access network (RAN). The service area of each RAN consists of several radio cells, each of which is the coverage area of a BS. The MSC is responsible for RRM, CAC, mobility management (MM), etc. The transmission between an MSC and the wireline backbone network is a wireline channel, while that between an MS and a BS is a wireless channel. There are two types of wireless channels: uplink, the link from MSs to a BS, and downlink, the link from a BS to MSs. The uplink channel is a multiple access channel, where all the MSs in the cell share the radio resources and compete for service. In the downlink channel, the BSs have the knowledge of the transmitted traffic. Communications between two or more users use the end-to-end transport through access networks and the wireline backbone network. The challenging issues behind supporting multimedia in wireless networks are the limited bandwidth, impairments in the propagation channel, and user mobility, which usually make the wireless access networks as the bottleneck in end-to-end transportation. This thesis is confined to the coverage area of the BSs under one MSC and assumes that the backbone network always has enough resources to serve all the connections admitted in the access networks. This research focuses on the uplink, since the uplink supports multi-user transmissions that impact on the capacity of the system.

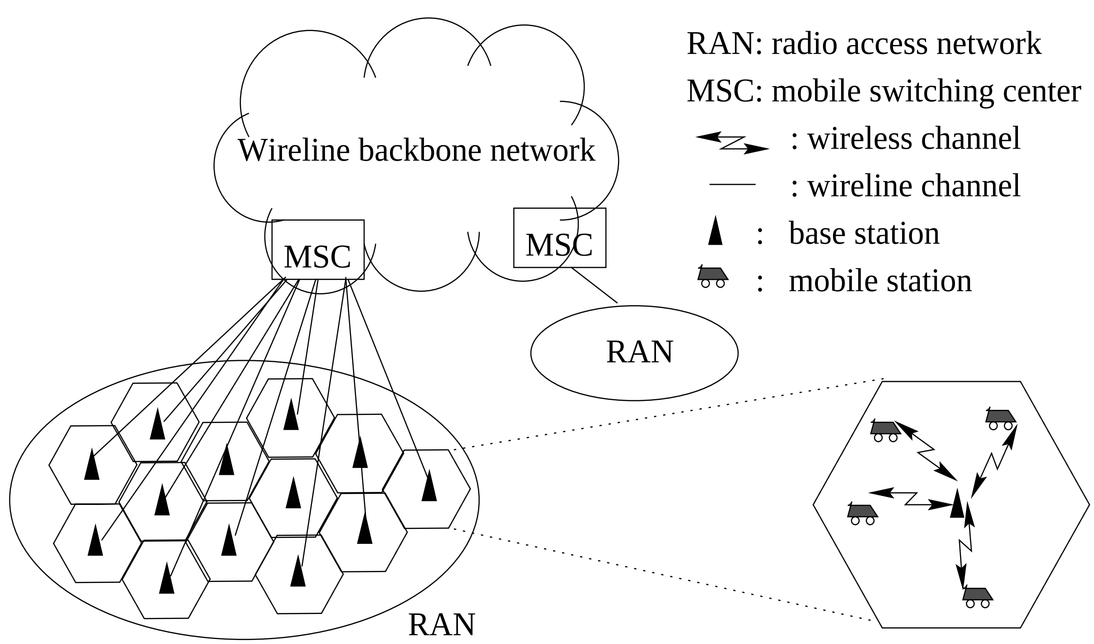

Figure 2.1: Integrated wireless/wireline network

2.2 CDMA system

We consider the case where the spread spectrum bandwidth, W, which is also the total system operation band, is shared by all the radio cells in the system. The isolation between uplink and downlink uses frequency-division-duplexing (FDD), where different frequency bands are used for uplink and downlink, so there is no interference from the downlink transmissions to the uplink transmissions. Transmission in each connection encounters background additive white Gaussian noise (AWGN), MAI from the transmissions of other connections in the same cell (intra-cell MAI), and MAI from the transmissions of the connections in other cells of the system (inter-cell MAI). The inter-cell MAI is characterized by the factor f, which is defined as the ratio of inter-cell MAI to intra-cell MAI, and assumed to be constant [31] [52]. Each MS chooses its associated BS based on the receiving signal strength.

The effect of soft handoff when an MS is communicating with two or more BSs on the uplink system performance is not explicitly considered in this research. In general, soft handoff helps to reduce the interference from users near the cell boundary and improve the system capacity. The amount of the capacity improvement depends on the specific power control algorithms and other link properties, such as path diversity. It has been shown in [31] that, when no multi-path diversity is used, soft handoff significantly reduces the MAI and improves the CDMA system capacity. However, when the order of path diversity is above 2, there is little improvement by using soft handoff [100].

2.3 Multi-rate and multi-code

Multi-code CDMA (MC-CDMA) [86] is adopted to support multi-rate transmissions because it has some advantages over other methods proposed in the literature. The multi-modulation CDMA [87] degrades the performance for the users with high data rates. When multiprocessing gain CDMA [88] is used, users with very high source rate have very small processing gain, because the chip rate is constant for all the users. Therefore, both multi-modulation CDMA and multiprocessing gain CDMA are biased against high data rate users, and the higher is the transmission rate, the lower is the communication quality. MC-CDMA is expected to work well with multimedia traffic. Because of its unified architecture, when it integrates multimedia traffic, traffic streams with significantly different transmission rates can be easily integrated with all the transmission channels having the same bandwidth and spread spectrum processing gain.

In an MC-CDMA system, all the data signals over the radio channel are transmitted at a basic rate, R_{b}. Any connection can only transmit at rates mR_{b}, referred to as m-rate, where m is a positive integer. Fig. 2.2 shows the block diagram of an MC-CDMA transceiver. When an MS needs to transmit at m-rate, it converts its data stream, serial-to-parallel, into m basic-rate streams. It first spreads each basic-rate stream with a different code and superimposes them before spread spectrum modulation. The multiple simultaneously transmitted packets from the same connection is first spread by a set of orthogonal codes generated by the so called "sub-code concatenation" scheme, and then spread by a long code B, which an MS uses to indicate the BS it is communicating with. The sub-code concatenation generated codes are unique to each mobile, while the long code is unique to each radio cell. The block diagrams

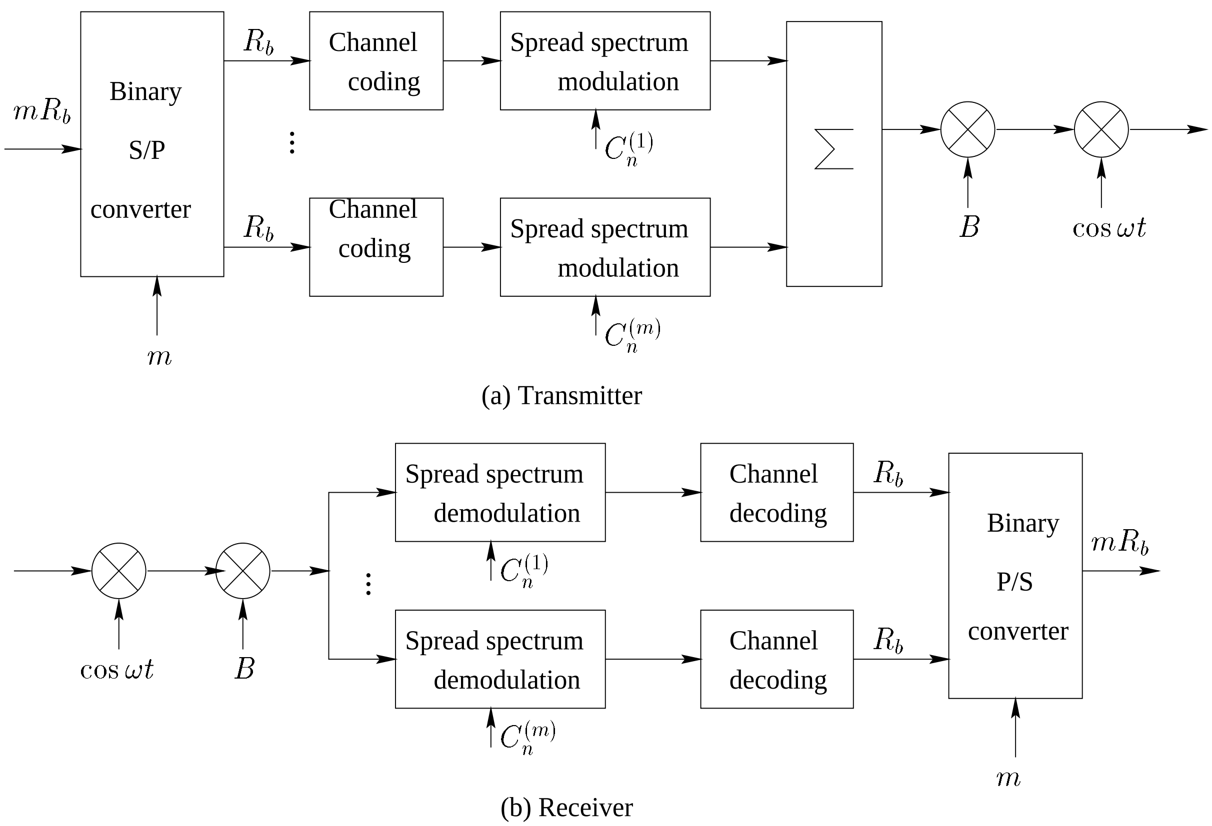

Figure 2.2: MC-CDMA transmitter and receiver

for modulation and demodulation are shown in Fig. 2.3, where BPSK modulation is assumed.

2.4 Power control

In a CDMA system, the available system resource is shared by all active users. An appropriate amount of power resource should be distributed to each connection to ensure its required SINR and at the same time to allow more active users in the system. Power control is necessary to maintain all users' signal powers at the desired target values at the BS receiver input. We focus on how much the required target

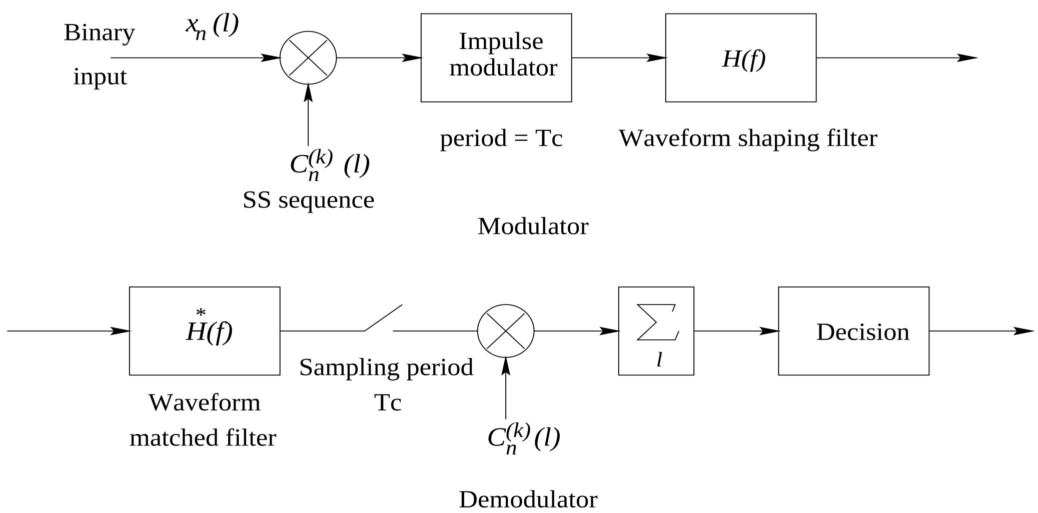

Figure 2.3: Spread spectrum modulation and demodulation

power is for each connection with given SINR requirements. The detail of how to implement the power control is beyond the scope of this research. There are methods for power control reported in the literature, e.g. [51]. Ideally, if perfect power control can be achieved, the required SINR for each user can be guaranteed by accurately distributing the received power for all the users, as long as the traffic load is within the system capacity. In reality, however, due to channel estimation errors, power control delay, power control command transmission errors, etc., imperfection in power control always exists.

The BS measures the average received power from an MS over a period (e.g., 0.625 ms for W-CDMA and 1.25 ms for cdma2000). After comparing the average value with the target power, a power control command is sent to the MS to raise or lower transmission power. With this process, power control can overcome the effect of the path loss and most of the effect caused by slow varying log-normal shadowing. We assume that with well-designed receiver structure, e.g. a RAKE receiver, the fast fading can be ideally mitigated. Therefore, the actual received power under imperfect power control is a random variable and follows a log-normal distribution according to the simulation results in [52].

2.5 Multiple access

The MAC protocol resolves contention resulting from the radio band sharing between a number of users. The frame architecture of uplink and downlink is shown in Fig. 2.4. Each uplink frame is divided into a minislot for downlink packet transmission acknowledgment, a contention-based Request Access minislot, a piggyback rate-request minislot, and a packet transmission slot. Multiple orthogonal code channels and corresponding receivers are assigned for the Request Access minislot. Transmissions at the Request Access minislot may be received erroneously at the BS due to interference or noise, or due to that different transmission requests selected the same code channels.

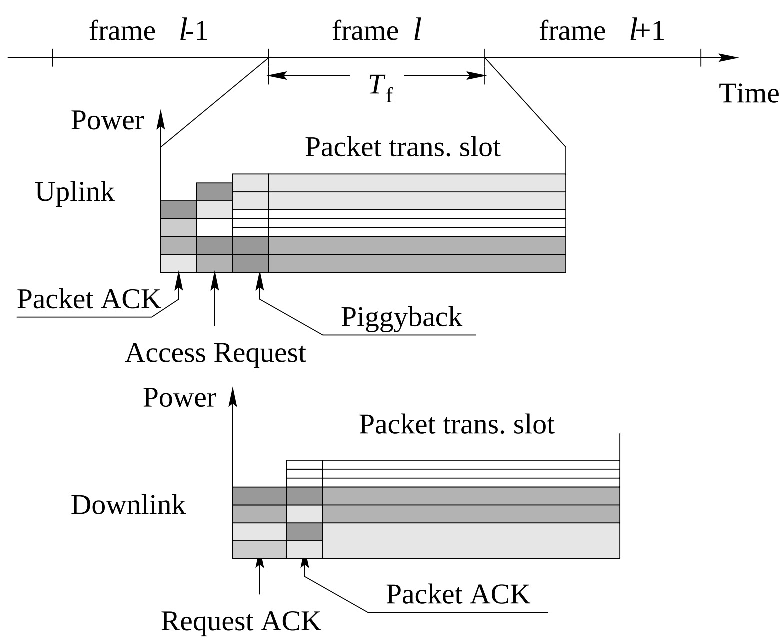

Figure 2.4: Uplink and downlink frame architecture

Approaches such as harmonic backoff [53] and binary stack algorithm [54] can be used to achieve reasonably high throughput and low request access delay. Each downlink frame is divided into an Request Ack minislot for contention-based transmission-requests, a minislot for uplink packet-transmission acknowledgment and for uplink packet transmission permission, and a downlink packet transmission slot. Data packet transmission coincides with the beginning of a packet transmission slot. Different connections can transmit simultaneously in one packet transmission slot, and one connection can also transmit multiple packets in one packet transmission slot. The satisfaction of QoS for the connections admitted in the system is guaranteed by CAC. However, when the amount of the available resources is more than just to provide guaranteed QoS, higher transmission rate can be provided for non-real-time traffic in the system through a packet scheduling scheme.

2.6 CAC and MM

The CAC makes admission decisions for new and handoff connections. It is performed at the MSC instead of at each BS, because making an admission decision for a new or handoff connection requires information about the MSs and traffic load in the entire RAN. Handoff requests are given a higher priority than new requests by reserving an appropriate amount of system resources for potential handoff connections. An admission decision is based on the traffic parameters and required QoS from both the new/handoff request and the existing connections. The CAC admits a new connection as long as its required QoS and the QoS of ongoing connections can be guaranteed. The reserved resource for potential handoff connections can still be efficiently utilized at the packet level to increase the packet throughput of non-real-time traffic. The resource reservation process is based on user mobility information, which is collected by mobility management (MM). The function of the MM is to maintain a record of the positions of all the users in the system and provide the updated user position information during a connection.

2.7 Summary

The system model and research scope have been defined in this chapter. MC-CDMA is used to support multi-rate transmissions in the cellular CDMA system. How to allocate the transmission rate and power to the simultaneous users so that the required QoS can be guaranteed while more users can be supported is an important issue in the RRM research. Traffic definition and resource allocation formulation are discussed in the next chapter.

Chapter 3

Problem Formulation

3.1 Problem statement

Consider the uplink operation in a cellular network. Before transmitting any packets, a user makes a connection request to the system. Upon receiving the connection request, the CAC at the MSC makes the decision about whether its connection can be admitted or not. The admission decision is made based on the declared traffic parameters and the required QoS performance in the connection request from the user, and the available resources in the system. The admission decision is then sent back from the MSC to the MS's currently associated BS which notifies the MS about whether or not its connection request can be accepted. If the admission decision is to accept, a connection can be made between the user and the BS before packet transmissions. Fig. 3.1 shows the state diagram of a connection since its arrival. The entire traffic is divided into different traffic classes, each of which is a group of all the connections with the same traffic parameters and QoS requirements. The new connection arrival process for each class is assumed to be a Poisson process. Assume that an MS can be in any of the radio cells with equal probability when it originates a connection. Each new connection request is subjected to a new connection admission test at the BS. Failure of the test results in connection blocking, and the probability of this is defined as new connection blocking probability (NCBP). After successfully passing the admission test, a connection is established between the user and the BS for packet transmission. The connection duration in each traffic class is assumed to be exponentially distributed. During the lifetime of its connection, the mobile user may move from place to place. When it migrates from the coverage area of one BS to that of another, handoff occurs. Whether or not the new BS can accept the connection is subjected to another admission test for the handoff connection. Failure of the test results in connection dropping, and the probability of this is defined as handoff connection dropping probability (HCDP). Dropping an ongoing connection is undesirable, compared to blocking a new connection. Therefore, the system should keep lower HCDP than NCBP, so that a majority of the admitted connections can finish their transmissions before leaving the system. To achieve this, admission tests should give a higher priority to a handoff connection than to a new connection. The higher priority can be achieved by reserving an appropriate amount of resources for potential handoff connections.

In most cases, there are a lot of connections in the system waiting for transmitting packets, as shown in Fig. 3.2. Each connection has one ready-to-transmit (RTT) buffer located at the MS, referred to as MS RTT buffer. Upon arrival, all the generated packets are temporarily stored in the MS RTT buffer before they can be transmitted. The time difference between the instant a packet arrives to and the instant it departs from the MS RTT buffer is its experienced delay. The delay variation with respect to the mean delay is called jitter. How to coordinate the packet transmissions from different connections so that the required QoS can be satisfied and high throughput can be achieved is the task of the packet scheduling. First-come-first-served is the simplest packet scheduling algorithm, but it cannot satisfy the strict QoS requirements for heterogeneous services. Real-time traffic is delay/jitter sensitive, and their packets must be transmitted more urgently than the packets from non-real-time traffic, i.e., the transmission rate for each real-time connection should be high enough to vacate the backlogged packets. On the other hand, some data traffic requires very low BER, although it can tolerate long delay. In this case, higher transmission powers are needed to ensure successful transmission with high probability. Also, a large buffer space is needed to store the delayed packets to avoid overflow. As long as the required QoS from each connection can be satisfied, the system should also transmit more packets from non-real-time traffic provided extra resources are available. Therefore, transmission rate allocation and power distribution are the basis for effective and efficient resource management, and should be performed based on the traffic parameters and required QoS performance from each connection.

There are four types of traffic under consideration: constant bit rate (CBR), variable bit rate (VBR), available bit rate (ABR), and unspecified bit rate (UBR). The terminology

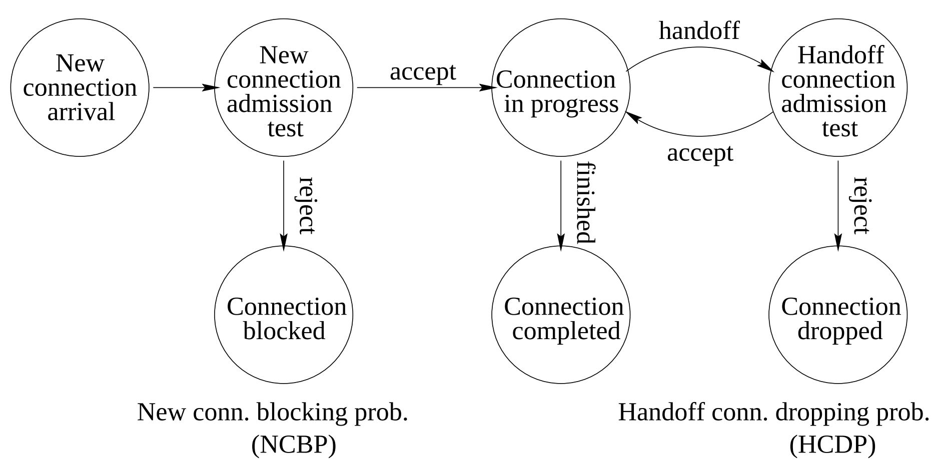

Figure 3.1: State diagram of a connection

of the traffic types is borrowed from the ATM Forum, but characterized in a slightly different way to formalize our problem. Each traffic type is further divided into classes. An ith class CBR connection (typically a voice connection) is characterized by a 3-tuple: $(\rho_i, \delta_i, \mathrm{BER}_i)$, $i = 1, 2, \cdots, K^c$, where ρ_i is the packet generation rate, δ_i is the maximum jitter tolerance, BER_i is the maximum tolerable BER, and K^c is the total number of CBR classes. Since the maximum jitter is limited by the maximum delay, D_i, only the maximum tolerable delay is considered. A CBR connection may contain both silent and active intervals. In the active intervals, it has a constant packet generation rate; while in the silent intervals, there is no packet generated. An ith class VBR connection (typically a video connection) is characterized by a 4-tuple: $(\rho_i, \sigma_i, D_i, \mathrm{BER}_i)$, $i = K^c + 1, K^c + 2, \cdots, K^c + K^v$, where ρ_i is the average packet generation rate, σ_i is the maximum packet burstiness, D_i is the maximum tolerable delay, BER_i is the maximum tolerable BER, and K^v is the total number of VBR

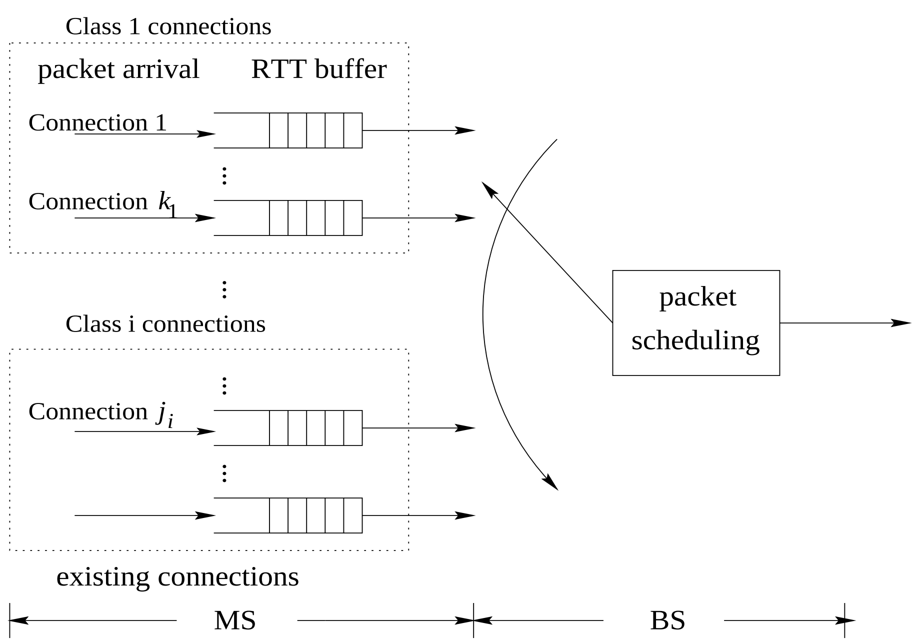

Figure 3.2: Block diagram for packet scheduling

classes. If a leaky bucket is used to regulate the ith class VBR connection, then the polling token generation rate and the polling token buffer size are equal to ρ_i and $(\sigma_i - 1)$, respectively. An ith class ABR connection (typically a data connection with minimum rate and BER requirements) can be characterized by a 2-tuple: (ρ_i, BER_i), $i = K^{\mathrm{c}} + K^{\mathrm{v}} + 1, K^{\mathrm{c}} + K^{\mathrm{v}} + 2, \cdots, K^{\mathrm{c}} + K^{\mathrm{v}} + K^{\mathrm{a}}$, where ρ_i is the minimum transmission rate, BER_i is the maximum tolerable BER, and K^{a} is the total number of ABR classes. An ABR connection can require higher transmission rate than its minimum rate, but the extra requests are served by best effort. A UBR connection (typically a data connection without any delay and BER requirements) has no QoS requirement, and it only needs best effort service. The system can assign a BER to the UBR connections with any value between 0 and 1. There is one UBR class, which includes all the UBR connections in the system.

Propagation delay in cellular networks is usually negligibly small (from a few μs to a few tens μs) compared to queueing delay ($>$ a few ms). As far as the uplink transmission is concerned, packet delay is mainly due to queueing delay in the MS RTT buffer. Bit errors include two parts, (i) bit errors due to channel noise and interference, and (ii) bit errors due to buffer overflow. Let p_i^{w} be the BER due to channel noise and interference, and p_i^{b} be the BER due to buffer overflow. Since the overflowed packets are not transmitted in the channel, the following equality holds [21]:

$$\mathrm{BER}_i = p_i^{\mathrm{b}} + (1 - p_i^{\mathrm{b}})p_i^{\mathrm{w}}, \tag{3.1}$$

i.e.,

$$p_i^{\mathrm{w}} = \frac{\mathrm{BER}_i - p_i^{\mathrm{b}}}{1 - p_i^{\mathrm{b}}}. \tag{3.2}$$

For given modulation and coding schemes, the required SINR at the BS receiver input for an ith class connection, γ_i^*, corresponds to the required BER due to signal propagation over the wireless channel, p_i^{w}.

Whether or not a packet transmission through the physical channel is successful depends on many factors. Random background noise, slow fading due to shadowing, fast fading due to multipath propagation, and MAI may cause erroneous transmissions. Impact of the physical transmission should be taken into consideration when dealing with the RRM in wireless cellular networks. Power control is an approach to overcome the channel fading in CDMA systems and to achieve the desired receive power.

3.2 Methodology and objective

In this research, a novel RRM scheme is proposed for cellular CDMA systems supporting heterogeneous services. The RRM scheme jointly takes the factors in the physical layer, link layer and network layer into consideration to achieve effective and efficient resource utilization. The resource utilization is defined at the connection level as the average number of connections in each traffic class that the system can support with guaranteed QoS for given offered traffic load. The basic approach to this RRM is summarized as follows.

The power distribution is a way to allocate power to all participating connections to maximize the number of simultaneously transmitting users subject to satisfaction of the SINR specifications. The power from each mobile should be large enough to achieve the required SINR for its connection, but should be kept low enough in order to reduce MAI to other connections in the same system, and to allow more active users in the system. We first study the power distribution under perfect power control, which represents the upper bound of the system performance. In a practical system, due to the channel estimation error, power control command transmission error, etc., some imperfection in power control always exists, which causes transmission performance degradation. Then, the power distribution under imperfect power control is studied. The effect of imperfect power control on the system performance is also investigated.

The power distribution is based on a given transmission rate from each participating connection. We then study how to allocate the transmission rate for each connection. The allocated transmission rate to each connection is determined by the packet generation rate, burstiness (for VBR connections), delay/jitter requirement, and loss rate (due to buffer overflow). A buffer with limited size should be allocated to each real-time (CBR or VBR) connection to temporarily store the delayed packets. The required buffer size may be also related to packet generation rate. A higher packet generation rate requires a larger buffer size. The rate allocation also makes use of the traffic randomness and burstiness and statistically multiplexes the traffic to achieve efficiency.

By proper power distribution and rate allocation, the required packet level QoS performance for each connection can be guaranteed, as long as the total traffic load is within the system capacity. How to schedule the packet transmissions from different connections is achieved by a packet scheduling scheme. The proposed packet scheduling scheme is based on the obtained power distribution and rate allocation, and is to guarantee the required QoS performance while improving the packet throughput for non-real-time traffic.

At the network layer, a CAC scheme is developed to achieve an effective and efficient admission control. The CAC scheme makes an admission decision for each connection based on the power distribution and the rate allocation, so that once admitted, the connection can be served with guaranteed QoS performance through packet scheduling. The CAC also incorporates the effect of mobile users' movement so that once admitted, the connection can be served with guaranteed QoS throughout its lifetime.

Lower HCDP is achieved by reserving an appropriate amount of system resource for potential handoff connections. Since the reserved resource cannot be used to admit any new connections, it is desired to reserve only the necessary amount of resources so that the NCBP would not be increased greatly, and the system resource utilization would not be decreased significantly. Handoffs are mainly caused by user movement. Intuitively, to keep the required low HCDP, the more likely the users will be handed off to a particular cell, the more resources should be reserved in that cell. Therefore, resource reservation in this CAC scheme is based on user mobility information.

By doing so, the objective of this research is to propose and to evaluate the performance of an effective and efficient RRM scheme which can:

(1) provide services to heterogeneous traffic with a wide range of parameters, including transmission rate and packet generation burstiness;

(2) guarantee a wide range of QoS levels, including delay/jitter requirements and BER requirements;

(3) utilize the radio resource efficiently at the link layer, i.e., improve the packet throughput for non-real-time traffic;

(4) achieve high resource utilization at the network layer, i.e., support more connections (or users) in the system;

(5) be implemented with reasonable complexity in practice.

Since some points of the objective are paradoxical, it is impossible to simultaneously optimize all of them. Our research is to improve the system utilization subject to satisfying a constraint on the others.

Chapter 4

Power Distribution

In this chapter, we study power distribution in CDMA systems to support heterogeneous services. The objective is to find a way of power distribution to maximize the number of simultaneously transmitting users for a given transmission rate and SINR requirement from each user. Both perfect power control and imperfect power control cases are considered.

4.1 Perfect power control case

Let θ_j be the index of the traffic class to which the jth connection belongs to, then $\theta_j = i$ if $\sum_{l=1}^{i-1} k_l < j \leq \sum_{l=1}^{i} k_l$, where $i = 1, 2, \ldots, K+1$, $j = 1, 2, \ldots, k^{\mathrm{t}}$, $k^{\mathrm{t}} = \sum_{i=1}^{K+1} k_i$, k_i is the number of connections in the ith class, and $K = K^{\mathrm{c}} + K^{\mathrm{v}} + K^{\mathrm{a}}$. Let $m_j R_{\mathrm{b}}$ be the transmission rate for the jth connection, where m_j is an integer, and S_j be the required power at the BS receiver input for the connection. The remaining part of this section is to find the minimum S_j so that the required SINR, $\gamma^*_{\theta_j}$, can be satisfied for all $j = 1, 2, \ldots, k^{\mathrm{t}}$, and more simultaneously transmitting users can be supported. At the BS receiver input, the MAI for any one of the m_j packets of the connection is given by

$$MAI_j = (1+f) \sum_{n=1, n\neq j}^{k^{\mathrm{t}}} m_n S_n, \tag{4.1}$$

where the factor f is the ratio of inter-cell MAI to intra-cell MAI. According to [89], for a rectangular pulse shaped baseband signal, the SINR at the BS receiver despread output for any one of the m_j packets can be expressed as

$$\gamma_j = \frac{3GS_j}{2(1+f)\sum_{n=1,n\neq j}^{k^{\mathrm{t}}} m_n S_n + 3GN_0 B_{\mathrm{b}}}, \tag{4.2}$$

where N_0 is the one-sided PSD of the background AWGN, $G = W/B_{\mathrm{b}}$ is the spread spectrum processing gain, B_{b} is the baseband bandwidth, and W is the spread spectrum bandwidth. To meet the required minimum SINR, $\gamma^*_{\theta_j}$, for the jth connection, the following condition must hold:

$$\gamma_j \geq \gamma^*_{\theta_j} \tag{4.3}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$. When equality holds in (4.3), the required receive power for each connection is minimized (see appendix B for proof), and the number of simultaneously transmitting users in each traffic class is maximized. Then, the following relationship is satisfied:

$$\frac{3G + 2(1+f)m_j\gamma^*_{\theta_j}}{2(1+f)\gamma^*_{\theta_j}} S_j - \sum_{n=1}^{k^{\mathrm{t}}} m_n S_n = \frac{3GN_0B_{\mathrm{b}}}{2(1+f)} \tag{4.4}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$. Solving this linear equation set yields

$$S_j = \frac{3GN_0B_{\mathrm{b}}\gamma^*_{\theta_j}}{[3G + 2(1+f)m_j\gamma^*_{\theta_j}]\Delta} \tag{4.5}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$, where Δ is given by

$$\Delta = 1 - \sum_{n=1}^{k^{\mathrm{t}}} \frac{2(1+f)m_n\gamma^*_{\theta_n}}{3G + 2(1+f)m_n\gamma^*_{\theta_n}}. \tag{4.6}$$

It should be noted that the above analysis is valid only when there are more than one connections in the system, i.e., MAI exists. When the total number of connection in the system is 1, the actual SINR for a connection at the BS despread output is given by

$$\gamma = \frac{GS}{N_0 W}. \tag{4.7}$$

Letting $\gamma = \gamma^*$, the required receive power for the connection is $S = \gamma^* N_0 R_b$. The required transmission power from the MS carrying the jth connection, P_j^{t}, can be calculated as $P_j^{\mathrm{t}} = S_j (d_j)^\alpha$, where d_j is the distance between the BS and the MS's current location, and α is the path loss exponent. The value of P_j^{t} should be positive and within the limit of the MS's maximum transmission power, P_j^{m}. Typical value of α, usually obtained by measurement, is between 2.7 and 5.

4.2 Imperfect power control case

When power control is imperfect, the actual receive power is assumed to be log-normally distributed. Suppose the target receive power for a transmitted packet from the jth connection in the θ_jth traffic class is $S_j^{'}$, then the actual receive power for the packet is $S_j^{'} e^{\beta X_j}$ due to imperfect power control, where $\beta = \ln(10)/10$, and X_j is a normally distributed random variable (r.v.). Let p^{i} be the outage probability due to imperfect power control in the system, which is the same for all the connections. If we assume that all the users use the same power control algorithm, the statistics of the channel transmission conditions are the same for all the users, and each user transmits independently, then we can consider that all X_j's are independent and identically distributed (i.i.d.). The mean and variance of X_j are $\mathrm{E}[X_j] = 0$ and $\mathrm{Var}[X_j] = \sigma_x^2$, respectively, for all $j = 1, 2, \ldots, k^{\mathrm{t}}$. The standard deviation, σ_x, of X_j represents the power control errors, and its unit is dB. Similar to the analysis in the previous section, the MAI experienced by any one of the m_j packets from the jth connection at the BS receiver is given by:

$$MAI'_j = (1+f) \sum_{n=1, n\neq j}^{k^{\mathrm{t}}} m_n S'_n e^{\beta X_n}. \tag{4.8}$$

At the BS receiver despread output, the SINR for any one of the m_j packets from the jth connection can be expressed as

$$\gamma_j = \frac{3GS'_j e^{\beta X_j}}{2(1+f)MAI'_j + 3GN_0B_{\mathrm{b}}}. \tag{4.9}$$

When the condition $\gamma_j \geq \gamma^*_{\theta_j}$ is satisfied, the communication is successful, i.e.,

$$\frac{3GS'_j e^{\beta X_j}}{2(1+f)MAI'_j + 3GN_0B_{\mathrm{b}}} \geq \gamma^*_{\theta_j}. \tag{4.10}$$

Replacing MAI'_j in (4.10) by (4.8) and manipulating, we have

$$\left[\frac{3G}{(1+f)\gamma^*_{\theta_j}} + 2m_j\right] S'_j e^{\beta X_j} - \sum_{n=1}^{k^{\mathrm{t}}} 2m_n S'_n e^{\beta X_n} \geq \frac{3GN_0B_{\mathrm{b}}}{1+f}. \tag{4.11}$$

The left-hand side of (4.11) is the sum of many independent log-normal r.v.'s. Therefore, the sum also approximately follows a log-normal distribution [90, 91]. Now, let

$$e^{\mathbf{\Psi}_j} = \left[\frac{3G}{(1+f)\gamma^*_{\theta_j}} + 2m_j\right] S'_j e^{\beta X_j} - \sum_{n=1}^{k^{\mathrm{t}}} 2m_n S'_n e^{\beta X_n} \tag{4.12}$$

where $\mathbf{\Psi}_j$ is a normally distributed r.v. with mean $M_{\mathbf{\Psi}_j}$ and variance $D^2_{\mathbf{\Psi}_j}$ to be derived later. Condition (4.11) can be further rewritten as

$$e^{\mathbf{\Psi}_j} \geq \frac{3GN_0B_{\mathrm{b}}}{(1+f)}. \tag{4.13}$$

To guarantee the required outage probability, p^{i}, the following condition should be satisfied:

$$\Pr\{\gamma_j < \gamma^*_{\theta_j}\} \leq p^{\mathrm{i}}, \tag{4.14}$$

which is equivalent to

$$\Pr\left\{\mathbf{\Psi}_j < \ln\left[\frac{3GN_0B_{\mathrm{b}}}{(1+f)}\right]\right\} \leq p^{\mathrm{i}}. \tag{4.15}$$

When equality holds in (4.15), each connection is distributed the minimum amount of power, and the number of simultaneously transmitting users in each traffic class is maximized. In this case, the following relationship holds:

$$p^{\mathrm{i}} = \Pr\left\{\mathbf{\Psi}_j < \ln\left[\frac{3GN_0B_{\mathrm{b}}}{(1+f)}\right]\right\}. \tag{4.16}$$

Since $p^{\mathrm{i}} < 0.5$ for a practical communication system, $M_{\mathbf{\Psi}_j} > \ln\left[\frac{3GN_0B_{\mathrm{b}}}{(1+f)}\right]$ must be true. Therefore, (4.16) can be rewritten as

$$p^{\mathrm{i}} = \mathrm{Q}\left[\frac{M_{\mathbf{\Psi}_j} - \ln\left[3GN_0B_{\mathrm{b}}/(1+f)\right]}{\sqrt{D^2_{\mathbf{\Psi}_j}}}\right] \tag{4.17}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$, where $\mathrm{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{x^2}{2}}dx$. Since both $M_{\mathbf{\Psi}_j}$ and $D^2_{\mathbf{\Psi}_j}$ are functions of $\{S'_j\}_{j=1}^{k^{\mathrm{t}}}$ (as will be derived later), solving equation set (4.17) yields $\{S'_j\}_{j=1}^{k^{\mathrm{t}}}$.

The remaining part of the section is to derive $M_{\mathbf{\Psi}_j}$ and $D^2_{\mathbf{\Psi}_j}$. First, the moments of $e^{\beta X_j}$ can be found as (see Appendix D)

$$M_X = \mathrm{E}[e^{\beta X_j}] = e^{\frac{1}{2}\beta^2\sigma_x^2}, \tag{4.18}$$

$$D^2_X = \mathrm{Var}[e^{\beta X_j}] = e^{\sigma_x^2\beta^2}(e^{\sigma_x^2\beta^2} - 1). \tag{4.19}$$

Then, fin the mean of both sides of (4.12) as

$$e^{M_{\mathbf{\Psi}_j} + \frac{1}{2}D^2_{\mathbf{\Psi}_j}} = F_j M_X \tag{4.20}$$

where

$$F_j = \frac{3G + 2(1+f)m_j\gamma^*_{\theta_j}}{(1+f)\gamma^*_{\theta_j}}S'_j - \sum_{n=1}^{k^{\mathrm{t}}} 2m_n S'_n. \tag{4.21}$$

Find the variance of both sides of (4.12) as

$$e^{2M_{\mathbf{\Psi}_j} + D^2_{\mathbf{\Psi}_j}}(e^{D^2_{\mathbf{\Psi}_j}} - 1) = H_j D^2_X \tag{4.22}$$

where

$$H_j = \frac{9G^2 - 4(1+f)^2 m_j^2 \gamma_{\theta_j}^{*2}}{(1+f)^2 \gamma_{\theta_j}^{*2}} S_j'^2 + \sum_{n=1}^{k^{\mathrm{t}}} 4m_n^2 S_n'^2. \tag{4.23}$$

Combining (4.22) and (4.20), we have

$$e^{D^2_{\Psi_j}} - 1 = \frac{H_j D_X^2}{F_j^2 M_X^2}. \tag{4.24}$$

Replacing M_X and D_X^2 by (4.18) and (4.19), respectively, reduces (4.24) to

$$e^{D^2_{\Psi_j}} - 1 = \frac{H_j(e^{\sigma_x^2 \beta^2} - 1)}{F_j^2}. \tag{4.25}$$

Then, $D^2_{\Psi_j}$ can be solved from (4.25) as

$$D^2_{\Psi_j} = \ln\left\{1 + \frac{H_j(e^{\sigma_x^2\beta^2} - 1)}{F_j^2}\right\}. \tag{4.26}$$

From (4.20) and (4.18), M_{Ψ_j} can be obtained as

$$M_{\Psi_j} = -\frac{1}{2} D^2_{\Psi_j} + \ln F_j + \frac{1}{2}\sigma_x^2 \beta^2. \tag{4.27}$$

Since both F_j and H_j are functions of $\{S_j\}_{j=1}^{k^{\mathrm{t}}}$, both M_{Ψ_j} and $D^2_{\Psi_j}$ are functions of $\{S_j'\}_{j=1}^{k^{\mathrm{t}}}$.

When there is only one user in the system, MAI does not exist. The actual SINR for the connection at the BS despread output is given by

$$\gamma = \frac{S' e^{\beta X}}{N_0 W}. \tag{4.28}$$

To guarantee the required outage probability, the following condition should be satisfied:

$$\Pr.\{\frac{S' e^{\beta X}}{N_0 W} < \gamma^*\} \leq p^{\mathrm{i}}, \tag{4.29}$$

which is equivalent to

$$\Pr.\{X < \frac{1}{\beta}\ln\left(\frac{\gamma^* N_0 W}{S'}\right)\} \leq p^{\mathrm{i}}. \tag{4.30}$$

Let equality hold in (4.30), the required target received power is given by

$$S' = \gamma^* N_0 W e^{\mathrm{Q}^{-1}(p^{\mathrm{i}})\sigma_x \beta}. \tag{4.31}$$

4.3 Numerical results

When the j_1th connection and the j_2th connection belong to the same class i, i.e., $\theta_{j_1} = \theta_{j_2} = i$, and $m_{j_1} = m_{j_2} = m_i$, $1 \leq j_i, j_2 \leq k^{\mathrm{t}}$, we have $S_{j_1} = S_{j_2} = S_i^{\mathrm{a}}$ for the perfect power control case. From (4.5) and (4.6) S_i^{a} can be obtained as

$$S_i^{\mathrm{a}} = \frac{3GN_0B_{\mathrm{b}}\gamma_i^*}{[3G + 2(1+f)m_i\gamma_i^*]\left[1 - \sum_{l=1}^{K}\frac{2(1+f)k_lm_l\gamma_l^*}{3G+2(1+f)m_l\gamma_l^*}\right]}. \tag{4.32}$$

For the imperfect power control case, if $\theta_{j_1} = \theta_{j_2} = i$, and $m_{j_1} = m_{j_2} = m_i$, $1 \leq j_i, j_2 \leq k^{\mathrm{t}}$, we have $F_{j_1} = F_{j_2} = F_i^{\mathrm{a}}$, $H_{j_1} = H_{j_2} = H_i^{\mathrm{a}}$, and $\Psi_{j_1} = \Psi_{j_2} = \Psi_i^{\mathrm{a}}$. Let $S_{j_1}^{'} = S_{j_2}^{'} = S_i^{\mathrm{a}'}$. Since it is difficult to obtain a closed form solution for $S_i^{\mathrm{a}'}$, the following procedure (taking $K = 3$ as an example) is used to calculate the numerical results of $S_i^{\mathrm{a}'}$, where $S_{\max}$ is the maximum possible value of all $S_i^{\mathrm{a}'}$, and is limited by the maximum transmission power of a mobile. $p^{\mathrm{i}*}$ is the actual required outage probability. The accuracy of the calculated powers is limited by the tolerable error, dp, and the step size, Dp.

1: Initialization. Let $S_i^0 = 0$ for $i = 1, 2, 3$;

2: Let $S_i^{\mathrm{a}'} = S_i^0$, for $i = 1, 2, 3$.

3: Calculate F_i^{a} and H_i^{a} using (4.21) and (4.23), $D_{\Psi_i}^{\mathrm{a}2}$ and $M_{\Psi_i}^{\mathrm{a}}$ using (4.26) and (4.27), and p^{i} using (4.17), for $i = 1, 2, \text{and } 3$.

4: If $p^{\mathrm{i}*} - dp \leq p^{\mathrm{i}} \leq p^{\mathrm{i}*} + dp$ for all $i = 1, 2, 3$, then $S_i^{\mathrm{a}'} = S_i^0$, for $i = 1, 2, 3$, and the process ends; otherwise, $S_1^0 = S_1^0 + Dp$.

5: If $S_1^0 \leq S_{\max}$, go to step 2; otherwise, $S_1^0 = 0$, and $S_2^0 = S_2^0 + Dp$.

6: If $S_2^0 \leq S_{\max}$, go to step 2; otherwise, $S_1^0 = S_2^0 = 0$, and $S_3^0 = S_3^0 + Dp$.

7: If $S_3^0 \leq S_{\max}$, go to step 2; otherwise, the process ends without a solution.

Let the standard deviation of imperfect power control, σ_x, be 1 dB. Fig. 4.1 shows the required receive powers for connections in different traffic classes as the number of voice connections increases. It can be seen from Fig. 4.1 that, as the traffic load increases, the required receive power increases for each traffic class. For a given traffic load, a voice connection requires the lowest receive power, compared with a video and a data connection, since a voice connection requires the lowest SINR and transmission rate. Fig. 4.1 also shows that, for a given connection, the required receive power is higher in the imperfect power control case compared with that in the perfect power control case.

To demonstrate the impact of imperfect power control on the required receive powers, Figs. 4.2-4.4 show the *Power Increase Factor* (PIF) for different traffic classes, where $\sigma_x = 1$ dB for imperfect power control case. The PIF is defined as the ratio of target power at the BS receiver input to achieve the same SINR value for a connection under imperfect power control to that under perfect power control, i.e.,

$$\mathrm{PIF}_i = \frac{S_i' \text{ under imperfect power control}}{S_i \text{ under perfect power control}} \tag{4.33}$$

It can be seen from Figs. 4.2-4.4 that the required receive power under imperfect power control is increased compared with that under perfect power control. The heavier the traffic load, the larger the PIF values. Furthermore, the PIF values for connections from different classes are almost the same, i.e., the impact of imperfect power control on the receive power is independent from the traffic classes. Intuitively, this is because the statistics of imperfect power control do not depend on different traffic classes. Fig. 4.5 shows that as the standard deviation of power control errors increases, PIF value increases significantly. Standard deviation of 0 dB represents the perfect power control case, while standard deviation between 1 and 2 dB should be good enough to model a practical power control case.

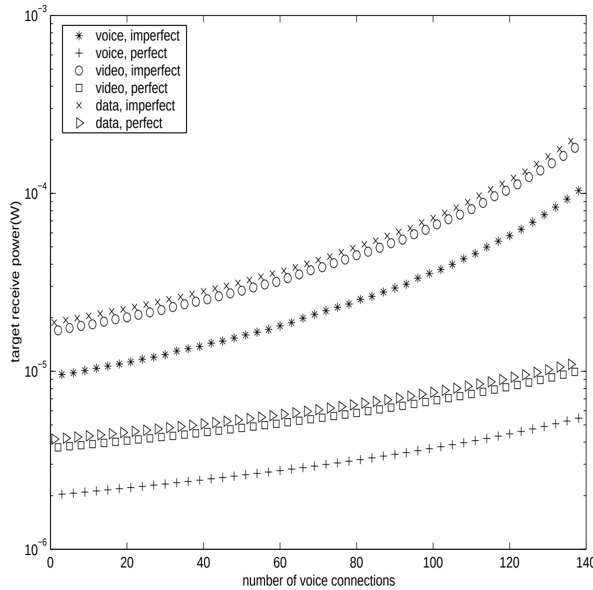

Figure 4.1: Required receive powers for different traffic classes

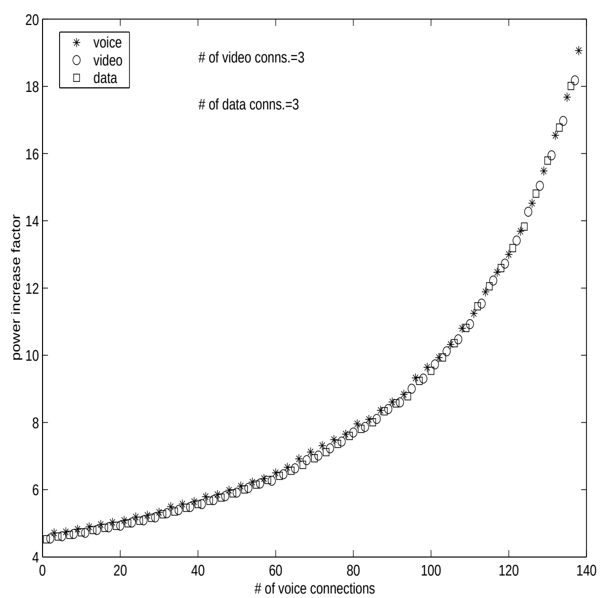

Figure 4.2: *Power Increase Factor* vs. number of voice connections

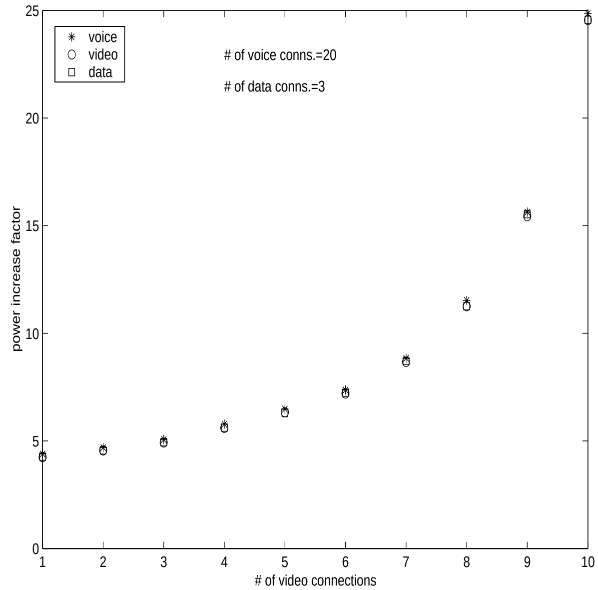

Figure 4.3: *Power Increase Factor* vs. number of video connections

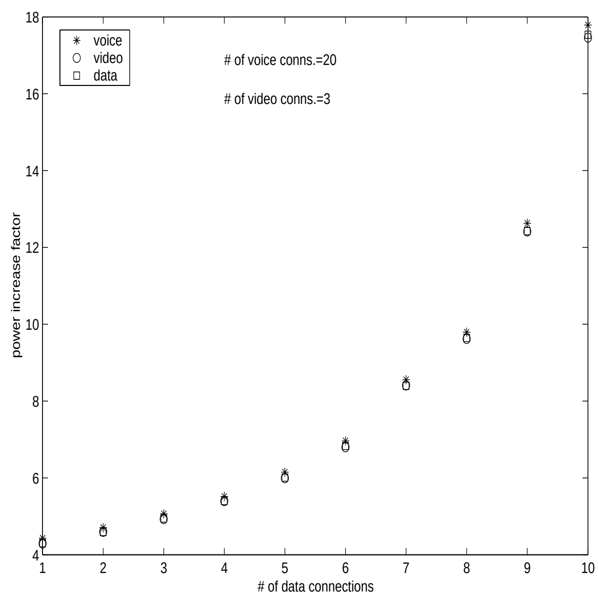

Figure 4.4: *Power Increase Factor* vs. number of data connections

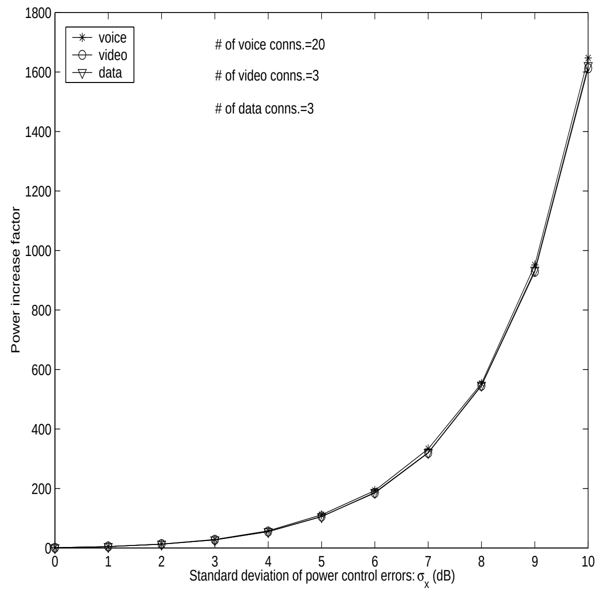

Figure 4.5: *Power Increase Factor* vs. power control imperfection

4.4 Summary

The required receive power at the BS has been derived for a CDMA system supporting heterogeneous services under perfect and imperfect power control cases, respectively. Numerical results have shown the impact of imperfect power control on the required receive power for each connection to achieve its required SINR performance compared with the perfect power control case. Power control imperfection increases the target received power for a connection in order to achieve the same QoS performance compared with the perfect power control case. The higher is the traffic load, the higher is the *Power Increase Factor*. It is also seen that, the *Power Increase Factor* does not depend on any particular traffic class. The power distribution is based on a given transmission rate. How to allocate the transmission rate for a connection is studied in the next chapter.

Chapter 5

Rate Allocation and Packet Scheduling

An appropriate power distribution can guarantee the required SINR for a given transmission rate from each user at a particular packet transmission slot. Sufficient transmission rate is required for a CBR or VBR connection to guarantee its required delay/jitter and loss requirement due to buffer overflow, and for an ABR connection to guarantee its minimum transmission rate. Besides, the transmission rates of some connections may change from time to time, e.g., a CBR connection may have both active and silent periods, and an ABR or UBR connection may require a different transmission rate in each time slot, the traffic load may change in different time slots. How to schedule the packet transmissions so that maximum packet throughput can be achieved while the required QoS performance for each connection can be guaranteed is the task of packet scheduling.

5.1 Rate allocation

This section develops a rate allocation mechanism for each class of the traffic in the system based on its required delay/jitter, loss rate due to buffer overflow, and packet generation rate and burstiness. Packet level traffic parameters are defined in section 3.1.

An ith class CBR connection can be modeled by an ON-OFF source, as shown in Fig. 5.1, where the ON and OFF states represent the active and the silent states of the CBR connection, respectively, a_i and b_i are the transition probabilities from the ON state to the OFF state and from the OFF state to the ON state, respectively, and A_i is the constant packet generation rate in the ON state. Both the ON and OFF intervals are assumed to be exponentially distributed. For each ith class CBR connection, its ON-OFF model parameter A_i equals ρ_i. In order to satisfy its strict delay constraint, a constant transmission rate equal to ρ_i is assigned to each ith class CBR connection during its active intervals. Such a rate allocation results in packet queueing delay bounded by the frame length of the system, T_f. If the buffer size B_i is equal to $T_\mathrm{f}\rho_i$, it can achieve zero packet loss rate due to buffer overflow, i.e., $p_i^\mathrm{b} = 0$. Therefore, this rate allocation is based on the condition $T_\mathrm{f} \leq D_i$, for all $1 \leq i \leq K^\mathrm{c}$. Since the typical delay tolerance is about 30ms for a voice connection, while the value of T_f is less than 10ms, the delay constraint of the CBR connection can be satisfied. During its silent intervals of the CBR connection, the allocated resource can be utilized by ABR and UBR connections through slot-by-slot packet scheduling.

For a VBR connection, a limited buffer size is needed due to its bursty packet generation process and stringent delay requirement. If the buffer size B_i is chosen to be D_iV_i, where V_i is the constant transmission rate assigned to the ith class VBR connection, then the maximum experienced delay is less than D_i for that connection. Let each ith

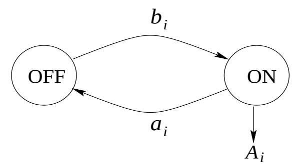

Figure 5.1: ON-OFF source model

class VBR connection be approximately represented by a superposition of N_i ON-OFF mini-sources as shown in Fig. 5.1. The effective transmission rate [93] V_i for the ith class VBR connection is given by:

$$V_i = A_i N_i \left[\tfrac{1-z_i}{2} + \sqrt{(\tfrac{1-z_i}{2})^2 + z_i \eta_i} \right], \tag{5.1}$$

where $\eta_i = \frac{b_i}{a_i+b_i}$ is the activity factor of the ON-OFF source, and $z_i = \frac{a_i B_i}{A_i(1-\eta_i)\ln(1/p_i^{\mathrm{b}})}$.

The assigned transmission rate for an ith class ABR connection is at least ρ_i. It is assumed that an ABR connection does not have any requirement on the experienced delay, and its buffer size is infinite, then the loss rate due to buffer overflow, p_i^{b}, for the ABR connection is zero.

In general, let $m_i^{\mathrm{a}} R_{\mathrm{b}}$ be the required transmission rate for the jth connection in order to achieve its required QoS, where $i = \theta_j$. Then m_i^{a} is given by

$$m_i^{\mathrm{a}} = \begin{cases} \lceil \rho_i / R_{\mathrm{b}} \rceil, & \text{when } \; i \le K^{\mathrm{c}} \;\; \text{(CBR)} \\ \lceil V_i / R_{\mathrm{b}} \rceil, & \text{when } \; K^{\mathrm{c}} < i \le K^{\mathrm{c}} + K^{\mathrm{v}} \;\; \text{(VBR)} \\ \lceil \rho_i / R_{\mathrm{b}} \rceil, & \text{when } \; K^{\mathrm{c}} + K^{\mathrm{v}} < i \le K \;\; \text{(ABR)} \\ 0, & \text{when } \; i = K+1 \;\; \text{(UBR)}. \end{cases} \tag{5.2}$$

The ceiling function $\lceil \cdot \rceil$ is required because the actual transmission rate in an MC-CDMA system is an integral multiple of R_{b}. For ABR and UBR connections, the actual transmission rate is determined according to the current traffic load through a packet scheduling scheme and may be larger than $m_i^{\mathrm{a}} R_{\mathrm{b}}$. The buffer size for the jth connection is $B_j = T_{\mathrm{f}} m_i^{\mathrm{a}} R_{\mathrm{b}}$ if $i = \theta_j \le K^{\mathrm{c}}$, and $B_j = D_i m_i^{\mathrm{a}} R_{\mathrm{b}}$ if $K^{\mathrm{c}} < i = \theta_j \le K^{\mathrm{c}} + K^{\mathrm{v}}$.

5.2 Packet scheduling scheme

Packet transmission requests are made through the Access Request minislot as shown in Fig. 2.4. Whether or not the requests can be accepted is determined by the packet scheduler. The purpose of the packet scheduling is two-fold: a) to determine the transmission rate for each ABR and UBR connection and the transmission power for all active connections in the system in order to achieve guaranteed QoS and b) to efficiently utilize the system resource on a time-slot basis and improve the packet throughput of the non-real-time traffic. The CBR and VBR connections do not need to request packet transmissions, since constant packet transmission rates are allocated to the connections according to the rate allocation policy in Section 5.1. The admitted ABR connections and the UBR connections request packet transmissions whenever their MS RTT buffers are not empty. Before each uplink packet transmission slot, the packet scheduler needs to allocate the transmission rate for each ABR and UBR connection in the system, and to calculate the required transmission power for all active connections in the system. Signaling for transmission requests and packet scheduling is transmitted through the minislots in each frame as shown in Fig. 2.4. Successful transmission requests are broadcast in the Request ACK minislot in the downlink before the next contention-based Access Request minislot. Prior to the arrival of each uplink packet transmission slot, the BS uses the Request ACK minislot to notify the CBR or VBR connections their assigned transmission powers, and to notify the ABR or UBR connections their assigned transmission powers and rates in the next uplink packet transmission slot. After sending the transmission permissions, the BS assigns a number of receivers so that they tune to the scheduled connections' code channels. When a connection is scheduled and permitted to transmit ABR or UBR packets in the packet transmission slot of the subsequent frame, it can use the piggyback minislot to update the required transmission rate for the next scheduled frame. Uplink packet transmissions are acknowledged through downlink Packet ACK minislot.

All packet transmission requests from the ABR connections wait in a first-come-first-served (FCFS) queue, indexed by $q = 1, \ldots, x^{\mathrm{a}}$, and all packet transmission request from UBR connections wait in another FCFS queue, indexed by $q = x^{\mathrm{a}}+1, \ldots, x^{\mathrm{a}}+x^{\mathrm{u}}$, where x^{a} and x^{u} are the total number packet transmission requests from ABR and UBR connections, respectively. For the transmission request in qth position in the FCFS queues, suppose it is from the j_qth connection in the i_qth class, where $i_q = K_1 + K_2 + 1, \ldots, K + 1$, and $j_q = 1, 2, \ldots, k^{\mathrm{t}}$. Let $m_q^{\mathrm{r}} R_{\mathrm{b}}$ be the required rate from the qth transmission request, $m_q^{\mathrm{s}} R_{\mathrm{b}}$ be the scheduled transmission rate, and S_j^{s} be the scheduled target receive power for the jth connection, where $j = 1, 2, \ldots, k^{\mathrm{t}}$. The values of m_q^{s} and S_j^{s} can be calculated using the following procedure.

Step 1: Let $q = 1$.

Step 2: Assign a transmission rate for each connection that will transmit packets in the next time slot, where each CBR and VBR connection is assigned its guaranteed rate as in 5.1, a connection having the qth packet transmission request is assigned its requested rate $m_q^{\mathrm{r}} R_{\mathrm{b}}$, the jth ABR or UBR connection having transmission request q_j is assigned its scheduled rate $m_{q_j}^{\mathrm{s}} R_{\mathrm{b}}$ if $q_j < q$, and is assigned its guaranteed rate $m_{\theta_j} R_{\mathrm{b}}$ if $q_j > q$. Let $\tilde{m}_j R_{\mathrm{b}}$ represent this temporarily assigned rate for the jth connection, then $\tilde{m}_j$ is given by

$$\tilde{m}_j = \begin{cases} m_{\theta_j}^{\mathrm{a}}, & \text{when } 1 \le \theta_j \le K^{\mathrm{c}} + K^{\mathrm{v}} \\ m_q^{\mathrm{r}}, & \text{when } j = j_q \\ m_{q_j}^{\mathrm{s}}, & \text{when } q_j < q, \ \& \ \theta_j > K^{\mathrm{c}} + K^{\mathrm{v}} \\ m_{\theta_j}^{\mathrm{a}}, & \text{when } q_j > q, \ \& \ \theta_j > K^{\mathrm{c}} + K^{\mathrm{v}}. \end{cases} \tag{5.3}$$

Step 3: The the minimum target power $\tilde{S}_j$ for connection j at the BS receiver input satisfies the following relationship given the above assigned rates.

$$\frac{3G\tilde{S}_j}{2(1+f)[\sum_{n=1}^{k^{\mathrm{t}}} \tilde{m}_n\tilde{S}_n - \tilde{m}_j\tilde{S}_j] + 3GN_0B_{\mathrm{b}}} = \gamma^*_{\theta_j}\epsilon_j \tag{5.4}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$, where

$$\epsilon_j = \begin{cases} 0, & \text{if } \tilde{m}_j = 0 \\ 1, & \text{otherwise.} \end{cases} \tag{5.5}$$

ϵ_j is used because the required power is zero if the transmission rate for a connection is zero. Solving (5.4) obtains the target receive power as

$$\tilde{S}_j = \frac{3GN_0B_b\gamma^*_{\theta_j}\epsilon_j}{[3G + 2(1+f)\tilde{m}_j\gamma^*_{\theta_j}]\Delta_q} \tag{5.6}$$

for $j = 1, 2, \ldots, k^{\mathrm{t}}$, where Δ_q is given by

$$\Delta_q = 1 - \sum_{n=1}^{k^{\mathrm{t}}} \frac{2(1+f)\gamma^*_{\theta_n}\epsilon_n}{3G+2(1+f)\tilde{m}_n\gamma^*_{\theta_n}\epsilon_n}. \tag{5.7}$$

$\Delta_q > 0$ should always be guaranteed to achieve positive required powers and avoid network congestion. If $\Delta_q \le 0$, the system cannot provide rate $m^{\mathrm{r}}_q R_{\mathrm{b}}$ from the qth request, and the process moves to Step 6; otherwise, continue Step 4.

Step 4: $\tilde{P}^{\mathrm{s}}_j = \tilde{S}_j\tilde{d}^{\alpha}_j$ is the transmission power from the MS carrying the jth connection. Let P^{m} be the maximum transmission power limit of each MS. If $\tilde{P}^{\mathrm{s}}_j < P^{\mathrm{m}}$ for all $j = 1, 2, \ldots, k^{\mathrm{t}}$, the requested transmission rate $m^{\mathrm{r}}_q R_{\mathrm{b}}$ can be provided, let $m^{\mathrm{s}}_q = m^{\mathrm{r}}_q$, and go to Step 6; otherwise, go to Step 5.

Step 5: Reduce the requested transmission rate by one basic packet transmission rate, i.e., let $m^{\mathrm{r}}_q = m^{\mathrm{r}}_q - 1$. If the new requested rate is still above the guaranteed rate, i.e., if $m^{\mathrm{r}}_q > m_{i_q}$, go back to Step 3. Otherwise, the rate is guaranteed by CAC for the ABR connection, and the process goes to Step 6.

Step 6: If $q = x^{\mathrm{a}} + x^{\mathrm{u}}$, the scheduled target receive power for each connection is $S^{\mathrm{s}}_j = \tilde{S}_j$, for $j = 1, 2, \ldots, k^{\mathrm{t}}$, and the process ends; otherwise, let $q = q + 1$, and go back to Step 2.

Packet scheduling for the imperfect power control case is similar but with more complexity to calculate the required transmission powers.

5.3 Example of packet scheduling

Let there be one class for each CBR, VBR and ABR, respectively. There are 6 active CBR connections, each requiring transmission rate R_{b}, 3 VBR connections, each requiring transmission rate $10R_{\mathrm{b}}$, and 2 ABR connections, each requiring a minimum transmission rate $8R_{\mathrm{b}}$. The required SINR for a CBR, VBR and ABR connection is 3.6 dB, 6.5 dB, and 8.6 dB, respectively. The first ABR connection requires an extra rate $8R_{\mathrm{b}}$, and the second ABR connection requires an extra rate $5R_{\mathrm{b}}$. The distance between each MS and the BS is $d_j = 0.5, 0.4, 1.1, 0.8, 0.7, 0.9, 1.0, 0.3, 0.8, 0.9, 0.4, 0.5$ km, $j = 1, 2, \ldots, 11$. Let the maximum transmission power for each MS be 0.1 W. Before the next uplink packet transmission slot, the packet scheduling performs the following procedure:

1.0 : Let $q_j = 1$ (the first ABR connection).

1.1 : Let

$$m_n' = \begin{cases} 1, & \text{when } 1 \leq n \leq 6 \ \text{(CBR)} \\ 10, & \text{when } 7 \leq n \leq 9 \ \text{(VBR)} \\ 8+8=16, & \text{when } n = 10 \ \text{(first ABR)} \\ 8, & \text{when } n = 11 \ \text{(second ABR)} \\ 0, & \text{when } n > 11 \end{cases} \tag{5.8}$$

1.2 : Calculate $\Delta_{q_j} = 0.068 > 0$.

1.3 : Calculate $0 < P_j^{\mathrm{s}} < 0.1$ W, $j = 1, 2, \ldots, 11$.

1.4 : Therefore, the first ABR connection is scheduled to transmit at $16R_{\mathrm{b}}$ in the next packet transmission slot.

2.0 : Let $q_j = 2$ (the second ABR connection).

2.1 : Let $m_{11}' = 8 + 5 = 13$, and calculate $\Delta_{q_j} = -0.011 < 0$.

2.2 : Let $m_{11}' = 12$, and recalculate $\Delta_{q_j} = 0.0029 > 0$.

2.3 : Calculate $0 < P_j^{\mathrm{s}} < 0.1$ W, $j = 1, 2, \ldots, 11$.

2.4 : Therefore, the second ABR connection is scheduled to transmit at $12R_{\mathrm{b}}$ in the next packet transmission slot.

5.4 Summary

Transmission rate allocation and packet scheduling for heterogeneous services have been proposed in this chapter. A real-time connection (CBR or VBR) is assigned a constant transmission rate, like in a circuit-switched system, to achieve the required small delay/jitter. Such an approach can also reduce the computational complexity when doing packet scheduling – no need of slot-by-slot rate allocation for the real-time connections. The rate allocation for a non-real-time connection (ABR or UBR) is scheduled slot-by-slot to efficiently utilize the available resource in each time slot and achieve high packet throughput. The rate allocation for a VBR connection makes use of the randomness and burstiness of its packet generation process to achieve high efficiency. UBR packets are transmitted when where is extra resources after transmitting all the CBR, VBR and ABR packets. Besides rate allocation, a packet scheduling scheme also calculates the required transmission power for each connection. The effectiveness and efficiency of the resource allocation is also closely related to an effective and efficient CAC scheme at the connection level.

Chapter 6

Connection Admission Control

Resource allocation at the connection level is to make an admission decision for a new or handoff connection upon receiving a connection request. A new or handoff CBR, VBR or ABR connection needs to request admission through the Access Request minislot (see Fig. 2.4) before it can transmit any packets. An admitted CBR connection requests reconnection for packet transmission after its silent intervals. It is crucial that the BS has the information about when the next active interval for the CBR connection will start so that the packets from the CBR connection will not be delayed after each silent interval. Although this problem will not be discussed in this thesis, the resource availability for the CBR connection is always guaranteed by the CAC scheme, because the CAC treats the CBR connection as an existing connection whether the connection is in its silent or active states. Upon receiving a CBR, VBR or ABR connection admission request, the BS forwards the request to the MSC, which makes an admission decision. The admission decision is then sent back from the MSC to the BS. If the connection is admitted, the admission decision is sent to the MS via the downlink Request ACK minislot. The BS also notifies the MS the allocated transmission rate if it is a CBR or VBR connection. A constant transmission rate is allocated to a CBR or VBR connection to ensure satisfaction of its delay/jitter requirement. A dedicated code channel and the corresponding receiver are allocated to each admitted CBR and VBR connection after the admission and released when the connection is completed, or handed off to a new cell. Therefore, no packet transmission requests are needed for an admitted CBR or VBR connection. The CAC guarantees that once admitted, the connection can be provided with satisfied delay/jitter and loss performance throughout the lifetime of the connection while the mobile is moving. The admission decision should also ensure low HCDP by resource reservation. A UBR connection does not request admission. It sends a packet transmission request whenever it has packets to transmit, but it is up to the system to decide whether or not the UBR connection can get the permission to transmit.

A CAC scheme is proposed in this chapter. QoS provisioning in the CAC is based on the rate allocation in Chapter 5 and the power distribution in Chapter 4. Handoff connections are given a higher priority in the CAC to reduce the HCDP by resource reservation. The resource reservation process is based on mobile users' mobility information. GOS performance, in terms of NCBP, HCDP, and resource utilization, is then derived.

6.1 Admission control

6.1.1 Admissible region

To admit a connection (new or handoff), two conditions must be satisfied: guaranteed packet level QoS for the particular connection should be satisfied, and packet level QoS performance of all the existing connections should also be ensured.

From the perspective of ensuring QoS requirements, the required transmission rates for the connections in the ith class, $m_i^{\mathrm{a}} R_{\mathrm{b}}$, are the same for all the connections in the same traffic class. Since the required SINRs for the connections in the same traffic class are also the same, the minimum required receive powers are the same for all the connections in the ith class, denoted as S_i^{a} for the perfect power control case, and $S_i^{\mathrm{a}'}$ for the imperfect power control case.

For the perfect power control case, S_i^{a} can be calculated according to (4.32) as follows:

$$S_i^{\mathrm{a}} = \frac{3GN_0 B_b \gamma_i^*}{(3G + 2f' m_i \gamma_i^*) \left[1 - \sum_{l=1}^{K} \frac{2f' k_l m_l \gamma_l^*}{3G+2f' m_l \gamma_l^*}\right]} \tag{6.1}$$

for $i = 1, 2, \ldots, K$. For the imperfect power control case, an algorithm similar to that in section 4.3 can be used to find the numerical results of $S_i^{\mathrm{a}'}$. Without confusion, in the remaining part of this subsection, we denote both S_i^{a} and $S_i^{\mathrm{a}'}$ as S_i^{a} for a simple presentation. The required transmission power at the MS for the jth connection can be calculated as

$$P_j^{\mathrm{a}} = S_{\theta_j}^{\mathrm{a}} (d_j)^{\alpha}. \tag{6.2}$$

Since the MS may move randomly during the lifetime of the connection, d_j is a r.v.. Therefore, P_j^{a} is also a r.v.. As the MS moves near the cell boundary, its required P_j^{a} value may be larger than the maximum transmission power limit of the MS, and communication outage occurs. Let p^{m} denote the outage probability due to the mobile users' movement and the limitation of the maximum transmission capability of the MS. In order to admit the connection, the following condition should be satisfied:

$$\Pr\left\{P_j^{\mathrm{a}} > P_j^{\mathrm{m}}\right\} = \Pr\left\{S_{\theta_j}^{\mathrm{a}} (d_j)^{\alpha} > P_j^{\mathrm{m}}\right\} < p^{\mathrm{m}}, \tag{6.3}$$

which can be further rewritten as

$$\Pr\left\{d_j > \left(S^{\mathrm{a}}_{\theta_j}/P^{\mathrm{m}}_j\right)^{\alpha}\right\} < p^{\mathrm{m}}. \tag{6.4}$$

for all $j = 1, 2, \ldots, k^{\mathrm{t}}$. The probability density function (pdf) of d_j is a function of both cell shape and user movement pattern, and can be found through either measurement or calculation. Then, the probability on the left-hand side of (6.4) can be calculated.

For a CDMA system supporting K traffic classes (CBR, VBR and ABR), an admissible state, $\mathbf{k}^{\mathrm{a}}$, which is a combination of the numbers of connections in each traffic class that can coexist in the system with guaranteed QoS, can be obtained based on the following calculations:

$$\begin{aligned} & \mathbf{k}^{\mathrm{a}} = (k^{\mathrm{a}}_1, k^{\mathrm{a}}_2, \ldots, k^{\mathrm{a}}_K), \quad k^{\mathrm{a}}_i \geq 0, \quad i = 1, 2, \ldots, K \\ \text{s.t.} \quad & \Pr\left\{d_j > \left(S^{\mathrm{a}}_{\theta_j}/P^{\mathrm{m}}_j\right)^{\alpha}\right\} < p^{\mathrm{m}}, \quad j = 1, 2, \ldots, k^{\mathrm{t}} \\ \text{and} \quad & S^{\mathrm{a}}_i > 0, \quad i = 1, 2, \ldots, K \\ \text{when} \quad & (k_1, k_2, \ldots, k_K) = (k^{\mathrm{a}}_1, k^{\mathrm{a}}_2, \ldots, k^{\mathrm{a}}_K) \end{aligned} \tag{6.5}$$

The admissible region of the system, $\mathbf{K}^{\mathrm{a}}$, is the set of all possible $\mathbf{k}^{\mathrm{a}}$, i.e., $\mathbf{K}^{\mathrm{a}} = \{\mathbf{k}^{\mathrm{a}}\}$.

6.1.2 Resource reservation

To achieve low HCDP, an appropriate amount of system resource is reserved for potential handoff requests. As long as the amount of the reserved resource is greater than 0, the resulted HCDP should be less than the NCBP since a higher priority is given to handoff connections than new connections. The more resource are reserved, the lower HCDP can be achieved. However, to save the precious radio resources, only the necessary amount of resource should be reserved, so that when a new connection arrives, there is enough resource to admit it. We propose that effective and efficient resource reservation for potential handoff connections should be based on user mobility information. Intuitively, to keep the required low HCDP, the more likely the users will be handed off to a particular cell, the more resource should be reserved in that cell. Since user mobility information changes with time, the resource reservation process should be updated periodically based on the current information. To achieve this, system time is divided into equal length intervals beginning at $t = 0, \tau, 2\tau, \ldots$. Smaller value of τ leads to frequent updating, while larger value of τ affects the accuracy of the reservation. The value of τ is chosen so that the probability of more than one handoff event for any MS in any interval of length τ is negligible. At the beginning of every interval of length τ, the handoff probabilities of each MS from its currently serving cell to its neighboring cells are assumed to be known to the MS's serving BS [77, 78]. Without loss of generality, let cell o be the reference cell. Define p_{bou} as the probability that MS u will be handed off from its current cell b to cell o in the next interval of length τ, then

$$h_i^\tau = \sum_{b \in B_o} \sum_{u \in \chi_{b,i}} p_{bou} \tag{6.6}$$

is the accumulated handoff probability of all the MSs carrying an ith class connection from the neighboring cells to cell o in the next interval of length τ, where B_o is the set of all the neighboring cells of cell o, and $\chi_{b,i}$ is the set of all the MSs carrying an ith class connection in cell b. The amount of the resources required by k_i^{h} ith class connections, $i = 1, 2, \ldots, K$, are reserved for the potential handoff requests in cell o, where $k_i^{\mathrm{h}} = \phi_i h_i^\tau$, and ϕ_i is a coefficient used to adjust the amount of reserved resources so as to achieve different HCDP values. The value of k_i^{h} is defined as the equivalent number of potential handoff connections. Theoretical relationship between the HCDP and ϕ_i's is derived in section 6.2.

6.1.3 Admission decision

When the BS in cell o receives a new or handoff connection request which belongs to the ξth traffic class, it allocates the connection a guaranteed packet transmission rate $m_\xi^{\mathrm{a}} R_{\mathrm{b}}$ according to (5.2), then check if $\tilde{\mathbf{k}}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}$ according to (6.5), where $\tilde{\mathbf{k}}^{\mathrm{a}}$ is given by

$$\tilde{\mathbf{k}}^{\mathrm{a}} = \begin{cases} (k_1 + k_1^{\mathrm{h}}, \ldots, k_\xi + k_\xi^{\mathrm{h}} + 1, \ldots, k_K + k_K^{\mathrm{h}}), & \text{for a new conn. admission} \\ (k_1, \ldots, k_\xi + 1, \ldots, k_K), & \text{for a handoff conn. admission} \end{cases} \tag{6.7}$$

and k_i is the actual number of existing ith class connections in cell o when the new or handoff connection requests for admission. If $\tilde{\mathbf{k}}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}$, the connection is accepted. Otherwise, the connection is rejected. From (6.7) it can be seen that the amount of resource required by k_i^{h} ith class connections, $i = 1, 2, \ldots, K$, is reserved for handoff connections, and cannot be used by new connections. In this way, the CAC gives a handoff connection a higher priority than a new connection.

It may happen that the system does not have enough resources to be reserved for all the potential handoff connections at some time according to the above criterion. However, for a particular connection, no sufficient reserved resources in a given cell does not affect the connection if it will not be handed off to the cell. As time goes by, some existing connections terminate their connections, then more resources can be released. The cell updates the resource reservation process in the next updating interval. The rule of resource reservation does not allow any new connection to be admitted unless there is enough reserved resource for all potential handoff connections. Therefore, as the system enters a steady state, there should be enough reserved resources for all the potential handoff connections.

6.2 Grade of service performance

The GOS performance, in terms of NCBP, HCDP, and resource utilization, is derived in this section. If the system traffic load and all the mobile users are uniformly distributed in all the cells, and the handoff probability of transiting into and out of every cell for each traffic class is the same, then the traffic characteristics and the GOS performance in each of the cells should be the same. In this way, we can consider a single cell and deal with the number of states needed to characterize its behavior. Suppose the connection arrival process follows a Poisson distribution with mean rate λ_i, and the connection duration is exponentially distributed with mean $1/\mu_i$ for the ith traffic class. Let $f_{T_i^{\mathrm{I}}}(t)$ be the pdf of the inter-handoff time, T_i^{I}, the time between two successive handoff events for a particular connection assuming that the holding time of the connection is infinitely large. To facilitate analysis, we approximate $f_{T_i^{\mathrm{I}}}(t)$ by an exponential distribution with parameter ν_i and obtain ν_i by solving the following equation [96]:

$$\int_0^\infty \left[f_{T_i^{\mathrm{I}}}(t) - \nu_i e^{-\nu_i t} \right] dt = 0. \tag{6.8}$$

Let p_i^{H} be the probability that an ith class connection will be handed off before the connection ends, then

$$p_i^{\mathrm{H}} = \int_0^\infty \nu_i e^{-\nu_i t} dt \int_t^\infty \mu_i e^{-\mu_i t'} dt' = \frac{\nu_i}{\mu_i + \nu_i}. \tag{6.9}$$

The probability p_i^τ that an ith class connection will be handed off to a new cell in the next interval of length τ is equal to the probability that the connection will be handed off to a new cell in an interval of length τ, and the probability that the remaining time of the connection is larger than τ. According to the memoryless property of an exponential distribution, p_i^τ can be calculated as

$$p_i^\tau = \int_0^\tau \nu_i e^{-\nu_i t} dt \int_\tau^\infty \mu_i e^{-\mu_i t} dt = (1 - e^{-\nu_i \tau}) e^{-\mu_i \tau}. \tag{6.10}$$

The cell dwelling time for the ith class connection is the time that the connection stays in the cell until it is handed off to a new cell or terminated, whichever comes first. Therefore, the dwelling time is also exponentially distributed with average $\frac{1}{\mu_i+\nu_i}$. At the connection level, the service system in each cell can be considered as a connection blocking system. The NCBP for the ith traffic class, p_i^{n}, is the probability that the system does not have enough resource to accommodate any additional ith class connections after serving all the existing connections and reserving resources for potential handoff connections. The HCDP for the ith traffic class, p_i^{h}, is the probability that the system does not have enough resource to accommodate any additional ith class connection after serving all the existing connections. The HCDP is the fraction of handoff attempts that are unsuccessful. There is also forced connection termination probability (FCTP) defined as the probability that a connection, after it is admitted into the system, is eventually forced to terminate due to insufficient resource when it is handed off to a new cell. The FCTP, p_i^{f}, for the ith traffic class can be calculated by

$$p_i^{\mathrm{f}} = \sum_{J=1}^{\infty}(p_i^{\mathrm{H}})^J(1-p_i^{\mathrm{h}})^{J-1}p_i^{\mathrm{h}} = \frac{p_i^{\mathrm{H}}p_i^{\mathrm{h}}}{1-p_i^{\mathrm{H}}(1-p_i^{\mathrm{h}})}, \tag{6.11}$$

where J represents the number of handoffs during the connection's lifetime. The system supporting K traffic classes can be modeled as a K-dimensional Markov chain [94]. As an example, Fig. 6.1 shows the state transition diagram of a cell with one traffic class (homogeneous traffic), where k^m is the maximum number of the homogeneous connections that the cell can support, and $k^h = \phi_1 k^m$ is the number of potential handoff connections that the cell reserves resources for.

For a system of supporting K traffic classes, the state transition probabilities are given by

$$\begin{cases} \Pr\{\mathbf{k}^{\mathrm{a}}|\mathbf{k}^{\mathrm{a}}-\mathbf{e}_i\} = \lambda_i + \lambda_i^{\mathrm{h}}, & \text{when } \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}} \ \& \ \mathbf{k}^{\mathrm{a}}+\mathbf{k}^{\mathrm{H}} \in \mathbf{K}^{\mathrm{a}} \ \& \ k_i^{\mathrm{a}} > 0 \\ \Pr\{\mathbf{k}^{\mathrm{a}}|\mathbf{k}^{\mathrm{a}}-\mathbf{e}_i\} = \lambda_i^{\mathrm{h}}, & \text{when } \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}} \ \& \ \mathbf{k}^{\mathrm{a}}+\mathbf{k}^{\mathrm{H}} \notin \mathbf{K}^{\mathrm{a}} \ \& \ k_i^{\mathrm{a}} > 0 \\ \Pr\{\mathbf{k}^{\mathrm{a}}-\mathbf{e}_i|\mathbf{k}^{\mathrm{a}}\} = k_i^{\mathrm{a}}(\mu_i+\nu_i), & \text{when } \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}} \ \& \ k_i^{\mathrm{a}} > 0 \end{cases} \tag{6.12}$$

for all $i = 1, 2, \ldots, K$, where $\mathbf{e}_i$ is a vector with the ith component equal to 1 and all the other $(K-1)$ components equal to zero, and $\mathbf{k}^{\mathrm{H}}$ is a vector representing the number of equivalent handoff connections in the next interval of length τ and is given by

$$\mathbf{k}^{\mathrm{H}} = (\phi_1 h_1^\tau, \phi_2 h_2^\tau, \ldots, \phi_K h_K^\tau) = (\phi_1 p_1^\tau k_1^{\mathrm{a}}, \phi_2 p_2^\tau k_2^{\mathrm{a}}, \ldots, \phi_K p_K^\tau k_K^{\mathrm{a}}). \tag{6.13}$$

Let $\pi(\mathbf{k}^{\mathrm{a}})$ be the equilibrium probability for the state $\mathbf{k}^{\mathrm{a}}$, we have

$$\sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}} \pi(\mathbf{k}^{\mathrm{a}}) = 1. \tag{6.14}$$

With (6.12) and (6.14), the equilibrium probability for the admissible state $\mathbf{k}^{\mathrm{a}} = (k_1^{\mathrm{a}}, k_2^{\mathrm{a}}, \ldots, k_K^{\mathrm{a}})$ is given by:

$$\pi(\mathbf{k}^{\mathrm{a}}) = \pi(\mathbf{0}) \prod_{i=1}^{K} \frac{[\varrho_i(\mathbf{k}^{\mathrm{a}})]^{k_i^{\mathrm{a}}}}{k_i^{\mathrm{a}}!}, \tag{6.15}$$

and

$$\pi(\mathbf{0}) = \left\{ \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}} \prod_{i=1}^{K} \frac{[\varrho_i(\mathbf{k}^{\mathrm{a}})]^{k_i^{\mathrm{a}}}}{k_i^{\mathrm{a}}!} \right\}^{-1}, \tag{6.16}$$

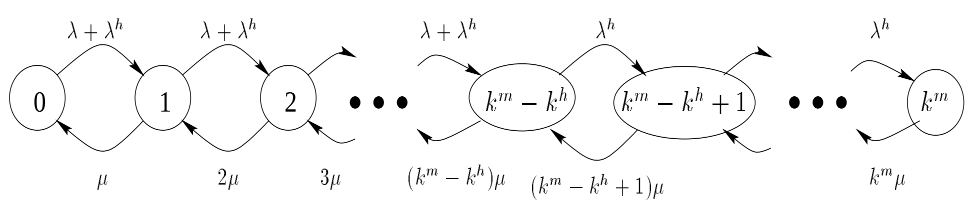

Figure 6.1: State transition diagram: $K = 1$

$\varrho_i(\mathbf{k}^{\mathrm{a}})$ is given by

$$\varrho_i(\mathbf{k}^{\mathrm{a}}) = \begin{cases} \frac{(\lambda_i+\lambda_i^{\mathrm{h}})}{\mu_i+\nu_i}, & \text{when } \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}} \;\;\&\;\; \mathbf{k}^{\mathrm{a}} + \mathbf{k}^{\mathrm{H}} \in \mathbf{K}^{\mathrm{a}} \\ \frac{\lambda_i^{\mathrm{h}}}{\mu_i+\nu_i}, & \text{when } \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}} \;\;\&\;\; \mathbf{k}^{\mathrm{a}} + \mathbf{k}^{\mathrm{H}} \notin \mathbf{K}^{\mathrm{a}} \end{cases} \tag{6.17}$$

for all $i = 1, 2, \ldots, K$, λ_i^{h} is the average handoff connection arrival rate for the ith traffic class and can be calculated as follows [97]

$$\lambda_i^{\mathrm{h}} = \frac{\nu_i(1-p_i^{\mathrm{n}})}{\mu_i + \nu_i p_i^{\mathrm{f}}}\lambda_i. \tag{6.18}$$

The NCBP for the ith class is given by

$$p_i^{\mathrm{n}} = 1 - \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{g}_i^{\mathrm{n}}} \pi(\mathbf{k}^{\mathrm{a}}) = 1 - \pi(\mathbf{0}) \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{g}_i^{\mathrm{n}}} \prod_{i=1}^{K} \frac{[\varrho_i(\mathbf{k}^{\mathrm{a}})]^{k_i^{\mathrm{a}}}}{k_i^{\mathrm{a}}!}, \tag{6.19}$$

where $\mathbf{g}_i^{\mathrm{n}}$ is given by

$$\mathbf{g}_i^{\mathrm{n}} = \{\mathbf{k}^{\mathrm{a}} | \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}, \mathbf{k}^{\mathrm{a}} + \mathbf{k}^{\mathrm{H}} + \mathbf{e}_i \in \mathbf{K}^{\mathrm{a}}\}. \tag{6.20}$$

The HCDP for the ith class handoff connection is given by

$$p_i^{\mathrm{h}} = 1 - \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{g}_i^{\mathrm{h}}} \pi(\mathbf{k}^{\mathrm{a}}) = 1 - \pi(\mathbf{0}) \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{g}_i^{\mathrm{h}}} \prod_{i=1}^{K} \frac{[\varrho_i(\mathbf{k}^{\mathrm{a}})]^{k_i^{\mathrm{a}}}}{k_i^{\mathrm{a}}!}, \tag{6.21}$$

where $\mathbf{g}_i^{\mathrm{h}}$ is given by

$$\mathbf{g}_i^{\mathrm{h}} = \{\mathbf{k}^{\mathrm{a}} | \mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}, \mathbf{k}^{\mathrm{a}} + \mathbf{e}_i \in \mathbf{K}^{\mathrm{a}}\}. \tag{6.22}$$

The resource utilization for the ith traffic class is given by

$$C_i = \sum_{k_i} k_i \pi_i(k_i), \tag{6.23}$$

where $\pi_i(k_i)$ is the probability that the number of ith class connections in the system is k_i and is equal to the ith marginal probability of the admissible state equilibrium probability when $k_i^{\mathrm{a}} = k_i$:

$$\pi_i(k_i) = \sum_{\mathbf{k}^{\mathrm{a}} \in \mathbf{K}^{\mathrm{a}}, k_i^{\mathrm{a}} = k_i} \pi(\mathbf{k}^{\mathrm{a}}). \tag{6.24}$$

In general, accurate calculation of $p_i^{\rm n}$, $p_i^{\rm h}$, C_i and $\pi(\mathbf{k}^{\rm a})$ is difficult because of the coupling among $\lambda_i^{\rm h}$, $p_i^{\rm h}$, $p_i^{\rm n}$ and $\pi(\mathbf{k}^{\rm a})$. $p_i^{\rm h}$ is usually very small in practice, e.g., $p_i^{\rm h} < 10^{-3}$. In this case, the FCTP, $p_i^{\rm f}$, is also very small and its effect on $\lambda_i^{\rm f}$ can be neglected, and (6.18) can be approximated as

$$\lambda_i^{\rm h} \approx \frac{\nu_i}{\mu_i}(1 - p_i^{\rm n})\lambda_i. \tag{6.25}$$

The following bisection algorithm can be used to find $p_i^{\rm n}$.

1: Let $x_i = 0$, $\text{Bin}_i = 1$, and $dp_i = \frac{1}{2}$ for $i = 1, 2, \ldots, K$.

2: Let $p_i^{\rm n} = x_i$ for $i = 1, 2, \ldots, K$.

3: Calculate $\lambda_i^{\rm h}$, $\varrho_i(\mathbf{k}^{\rm a})$, and $\pi(\mathbf{k}^{\rm a})$ from (6.25), (6.17), and (6.15), respectively.

4: Calculate $p_i^{\rm n}$ according to (6.19) for $i = 1, 2, \ldots, K$. Let $y_i = p_i^{\rm n}$.

5: If $|y_i - x_i| < \Delta^{\rm p}$ for $i = 1, 2, \ldots, K$, the process ends; otherwise, go to Step 6.

6: If $y_i > x_i$ and $\text{Bin}_i = 1$, let $x_i = x_i + dp_i$, for $i = 1, 2, \ldots, K$. If $y_i > x_i$ and $\text{Bin}_i = 0$, let $\text{Bin}_i = 1$, $dp_i = dp_i/2$ and $x_i = x_i + dp_i$, for $i = 1, 2, \ldots, K$. If $y_i < x_i$ and $\text{Bin}_i = 1$, let $\text{Bin}_i = 0$, $dp_i = dp_i/2$ and $x_i = x_i - dp_i$, for $i = 1, 2, \ldots, K$. If $y_i < x_i$ and $\text{Bin}_i = 0$, let $x_i = x_i - dp_i$, for $i = 1, 2, \ldots, K$. Go back to Step 2.

The proof of the existence of p_i^n is given in the appendix E for $K = 1$. The proof for $K > 1$ case is similar. Since a loss queueing system is always stable, the solution of $p_i^{\rm n}$ is also unique. The proof of the uniqueness of the solution is not given, and interested readers are referred to [126]. The value of $\Delta^{\rm p}$ in the algorithm is predefined and determines the accuracy of the calculation.

6.3 Summary

A CAC scheme has been proposed in this chapter. An admissible region is first defined based on the rate allocation and power distribution. Resource reservation for handoff requests is based on user mobility information to effectively reduce the HCDP while achieving efficient resource utilization. Because the admissible region can be calculated off-line given the traffic parameters and QoS requirements of each traffic class, the complexity of the CAC is greatly reduced. The system is then model as a K-dimensional Markov chain, and GOS performance is derived. Numerical results of the GOS are demonstrated in the next chapter.

Chapter 7

Numerical Results

The system parameters used in this numerical results are listed in Table 7.1.

Table 7.1: System parameters

spread spectrum BW W	5 MHz
basic multi-code rate R_{b}	16 kbps
system processing gain G	256
channel frame length T_{f}	10 ms
one-sided noise PSD N_0	10^{-8} W/Hz
channel attenuation factor α	3
MS maximum transmission power	0.1 W

There are three traffic classes, a voice, a video and a data class, and their traffic parameters are listed in Table 7.2. The block diagram of channel coding is shown in Fig. 7.1. Convolutional coding with rate $\frac{1}{3}$ and constraint length 9 is used as the channel coding for voice traffic. Concatenated convolutional coding (inner coding) and Reed-Solomon (RS) coding (outer coding) are used as the channel coding for both video and data traffic, where the convolutional code has rate $\frac{1}{2}$ and constraint length 9, and the RS code is a $(16, 12, 5)$ code, i.e., each symbol contains 5 bits, each codeword includes 16 symbols and 12 of them are information symbols. The bit rate in the ON state from the voice encoder (G.723 standard encoder) is 5.3 kbps, which is then input to the channel encoder for voice traffic. The output bit rate from the channel encoder for voice traffic is 16 kbps, which is equal to R_{b}. The activity factor η_i for a voice connection is $\frac{3}{8}$. The video connections are low bit rate for video phone (H.263 encoded). Each video connection is modeled by 14 ON-OFF mini-sources, each mini-source with $A_i = 4.8$ kbps, $a = 0.8$, and $b = 0.2$. The effective transmission rate for each video connection is 60 kbps before channel encoding, and 160 kbps after channel coding. Then, the allocated transmission rate for each video connection is $10R_{\mathrm{b}}$. The minimum required transmission rate for each data connection is 48 kbps before channel coding, and 128 kbps, or $8R_{\mathrm{b}}$, after channel coding. The loss rate due to buffer overflow, p_i^{b}, for a VBR connection is 2×10^{-6}. The relationship between the transmission BER and SINR performance for the selected coding schemes is given in Appendix A.

This chapter first presents numerical results of the GOS performance for a single cell network, then for a multi-cell cellular network. The difference between the two systems is that there is no handoff involved in the single cell system. Therefore, there is no need to reserve resource for handoff requests.

Table 7.2: Traffic parameters

three traffic classes	voice, video and data
average connection duration $1/\mu_i$	200 s
channel coding:	
voice	convolutional code
video	concatenated convolutional and RS
data	concatenated
transmission rate after coding $m_i R_\mathrm{b}$:	
voice	R_b
video	$10R_\mathrm{b}$
data	$8R_\mathrm{b}$
BER BER_i^*	
voice	10^{-3}
video	10^{-5}
data	10^{-7}
maximum delay tolerance D_i:	
voice	30 ms
video	80 ms

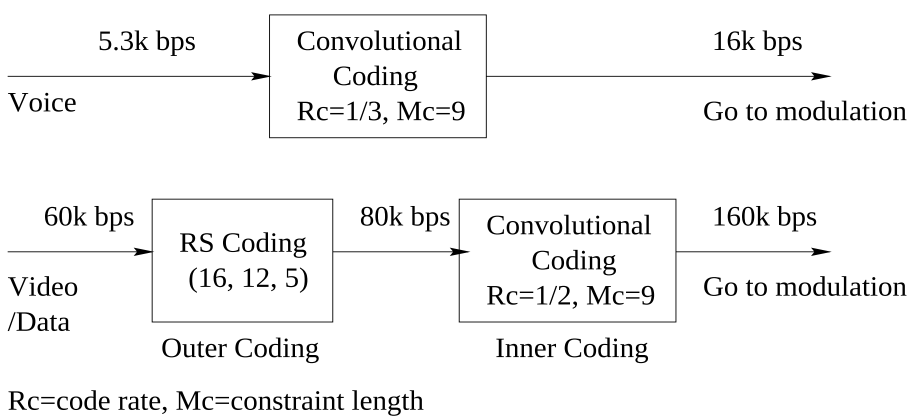

Figure 7.1: Block diagram of channel coding

7.1 Single cell systems

Let the cell size be 1200 m. Figs. 7.2-7.7 show the GOS performance of the system with the proposed RRM scheme.

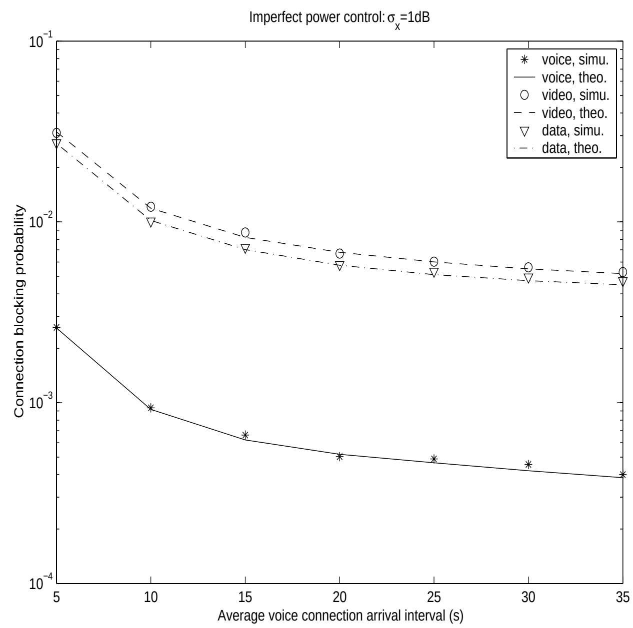

Figure 7.2: Comparison of NCBP between theoretical and simulation results

Comparison of NCBP between theoretical and simulation results is shown in Fig. 7.2, and that of resource utilization between theoretical and simulation results is shown in Fig. 7.3, where the average connection arrival interval for both video and data traffic is 20 s, and the standard deviation of power control errors is 1 dB. It can be seen that the simulation results verify the theoretical results very well.

Fig. 7.4 shows the NCBP vs. average voice connection arrival interval, where the average connection arrival interval for both video and data traffic is 20 s. Fig. 7.5 shows the NCBP vs. average video connection arrival interval, where the average connection arrival interval for voice and data traffic is 10 s and 20 s, respectively.

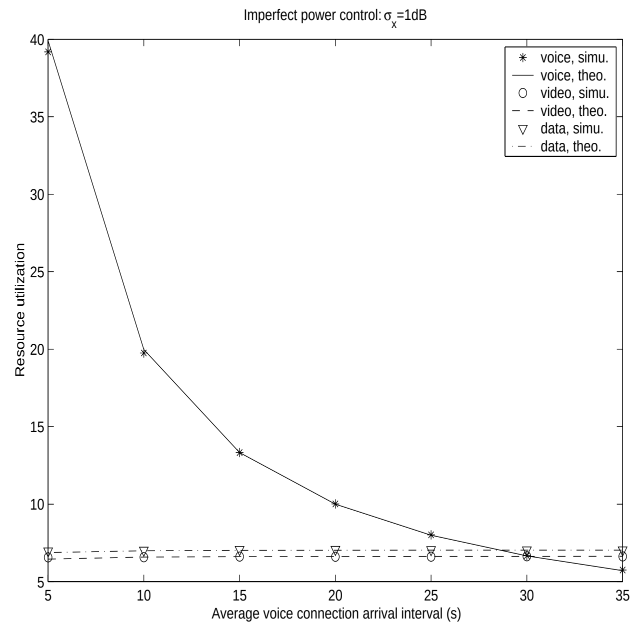

Figure 7.3: Comparison of resource utilization between theoretical and simulation results

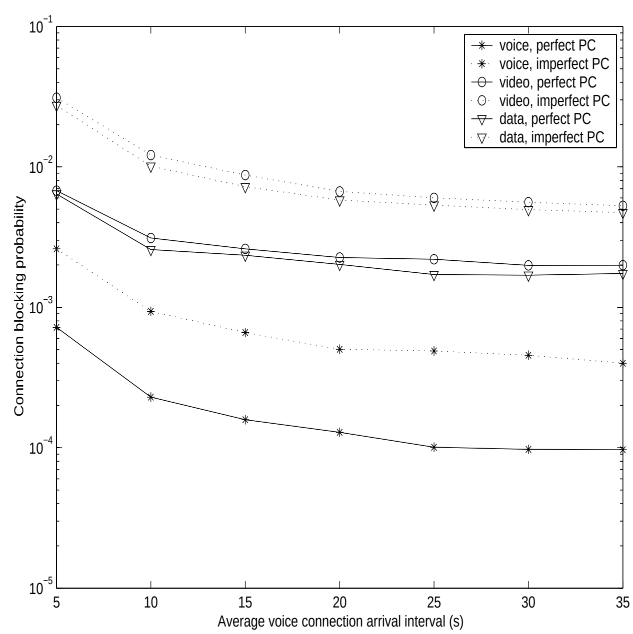

Figure 7.4: Comparison of NCBP under perfect and imperfect power control: vs. average voice connection arrival interval

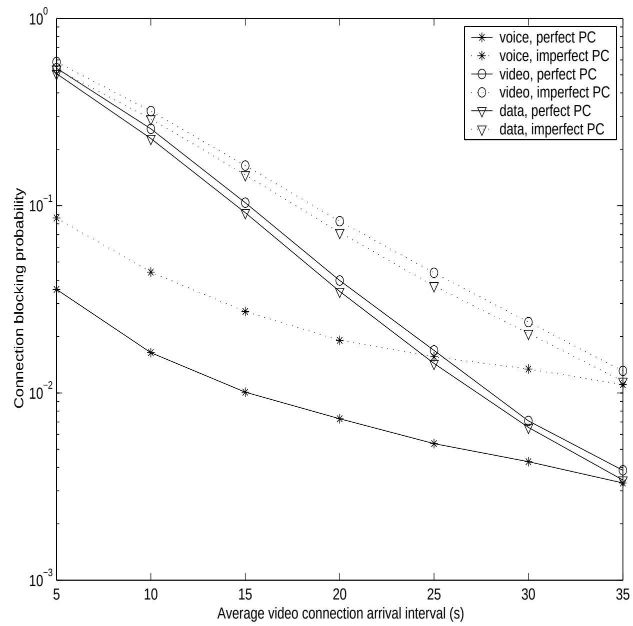

Figure 7.5: Comparison of NCBP under perfect and imperfect power control: vs. average video connection arrival interval

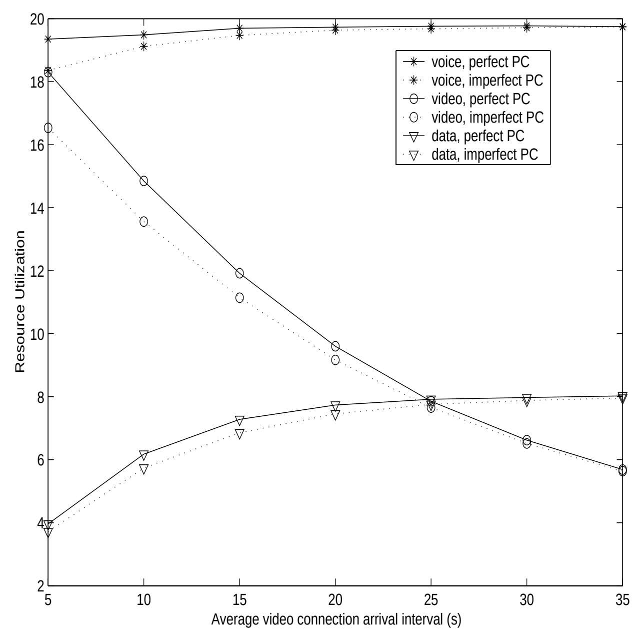

Figure 7.6: Comparison of resource utilization under perfect and imperfect power control

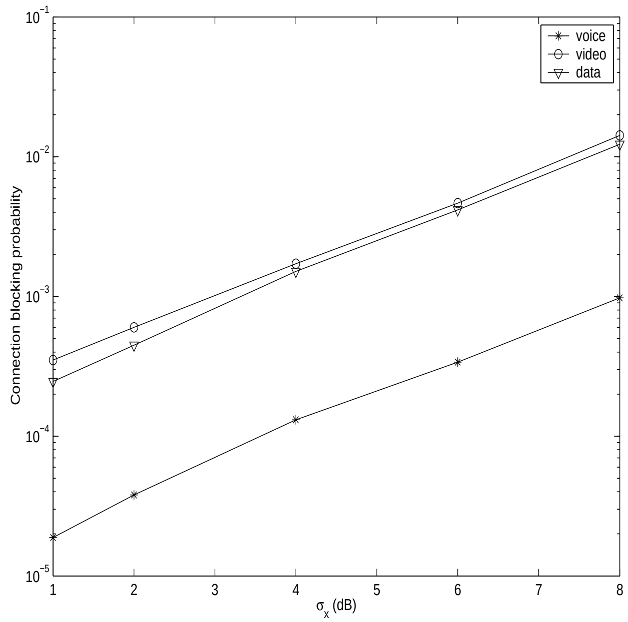

Figure 7.7: Effect of power control imperfection on NCBP

For both Figs. 7.4 and 7.5, the standard deviation of power control errors is 1 dB. Figs. 7.4 and 7.5 show that for each traffic class, NCBP is higher under imperfect power control, compared with that under perfect power control. This is because power control imperfection increases the required power at the BS receiver input in order to achieve the same SINR (see section 4.3). The figures also show that as voice connection arrival rate decreases, NCBP for each traffic class decreases slightly. While as video connection arrival rate decreases, NCBP for each traffic class decreases rapidly. The difference is due to the fact that a video connection requires much more resource than a voice connection.

Fig. 7.6 shows resource utilization vs. average video connection arrival interval, where the average connection arrival interval for both voice and data traffic is 10 s and 20 s, respectively, and the standard deviation of power control errors is 1 dB. Fig. 7.6 shows that resource utilization decreases for each traffic class under imperfect power control compared with that under perfect power control. It also shows that as the video connection arrival rate decreases, resource utilization for video traffic decreases significantly, while resource utilization for data traffic increases significantly and that for voice traffic increases slightly. This is because voice NCBP does not decrease much as the video connection arrival rate decreases.

Fig. 7.7 shows the effect of power control errors on the NCBP performance, where the average connection arrival interval for voice, video and data traffic is 10 s, 20 s, and 20 s, respectively. The figure shows that as the standard deviation of power control error increases, NCBP for each traffic class increases. Because of this, the resource utilization for each class decreases. Therefore, poor power control reduces the system GOS performance.

All the above figures also show that, when the connection arrival rate for one traffic class decreases (average arrival interval increases), NCBP for each traffic class decreases, because the available resources are shared by all the connections in the system. Besides, voice connections always receive better NCBP performance than video or data connections, because a voice connection requires much less resource than a video or data connection does.

When the connection arrival rate for voice traffic is very high, the NCBP for video and data may be very high. In this case, to overcome the significant unfairness of NCBPs among different traffic classes in the admission control, one approach is to block some new voice connections even when there is sufficient resource available for them. In this way, more resource can be left for new video or data connections. In the following "fair" admission control scheme, upon receiving a new connection request (belonging to class ξ), besides checking if the system state is still within the system admissible region by adding one more additional connection in class ξ, the system also checks the current blocking rate of each traffic class, which is defined as the ratio of the number of blocked connection requests to the number of all connection requests till the current moment for the particular class. If the blocking rate of the traffic class to which the new connection belongs is lower than the blocking rates of other traffic classes by a certain point (1% in this example), the connection request is blocked. Compared with the "fair" CAC, the proposed CAC in Chapter 6 is referred to as first-come-first-served (FCFS) CAC. Figs. 7.8 and 7.9 show the comparison between the "fair" CAC and the FCFS CAC, where the average connection arrival intervals for voice and data traffic are 10 s and 25 s, respectively. As can be seen from Fig. 7.9, the "fair" CAC can achieve fair NCBP by blocking new admission requests from connections requiring less resources. The NCBP of voice traffic has been increased a lot compared with the FCFS CAC, especially at high traffic loads, while the NCBP of video and data traffic does not decrease very much. It may also be seen that, by doing "fair" CAC, the resource utilization of voice traffic is greatly reduced, especially at high traffic load, while the resource utilization of video or data traffic does not increase much. The reason that the significant reduction in performance of voice traffic does not benefit the performance of video or data traffic very much is because a voice connection requires much less resource than a video or data connection. Therefore, it is concluded that, connection level fairness may not be necessary if the difference of required resource among different traffic classes is significant.

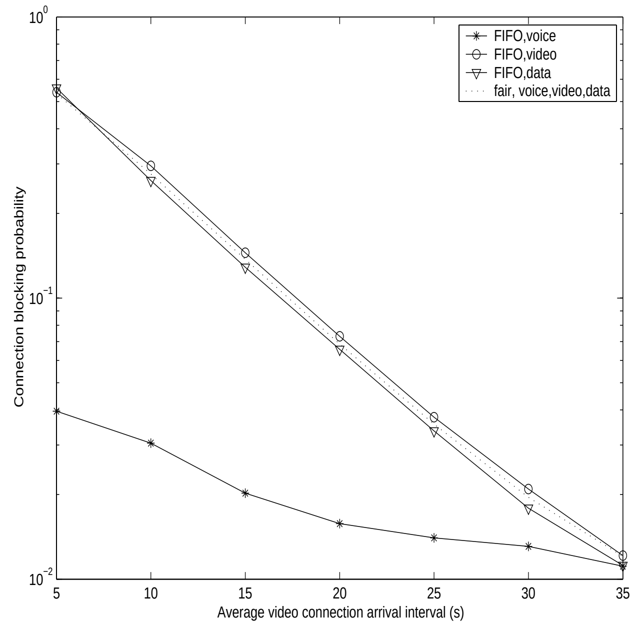

Figure 7.8: Comparison of NCBP between FCFS CAC and “fair” CAC

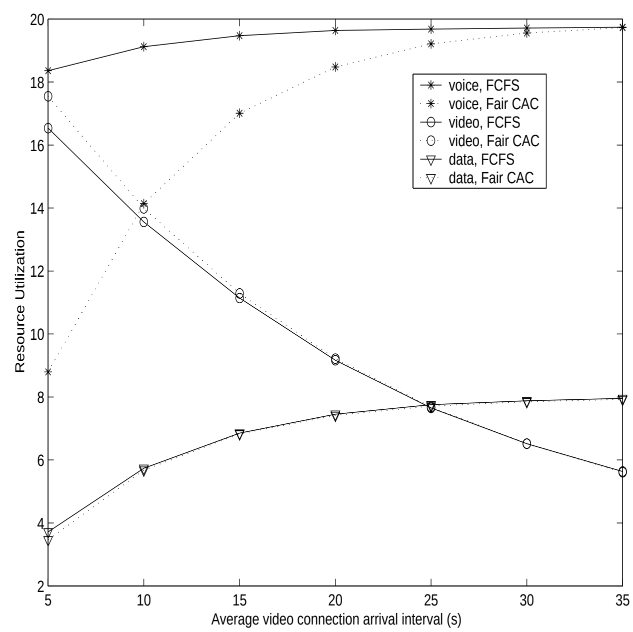

Figure 7.9: Comparison of resource utilization between FCFS CAC and “fair” CAC

7.2 Cellular systems

7.2.1 Simulation model

Without loss of generality, we consider a one dimensional (1-D) cellular array as shown in Fig. 7.10. All the cells in the network are arranged as a circle to avoid the boundary effect. At the time when an MS originates a new connection request, it can be in any one of the cells with equal probability. The initial location of an MS is uniformly distributed in the 1-D region of its cell. The mobile velocity v is uniformly distributed between $v_{\min}$ and $v_{\max}$. The movement direction can be either one of the two directions with equal probability. When an MS reaches the boundary of two cells, it randomly chooses a new direction and velocity. The probability distribution function $F_{T_i^{\mathrm{I}}}(t)$, of the connection inter-handoff time, can be found as follows:

$$\begin{aligned} F_{T_i^{\mathrm{I}}}(t) &= \Pr\{T_i^{\mathrm{I}} \le t\} = \Pr\{v \le L/t\} \\ &= \begin{cases} 1, & \text{when } t \ge L/v_{\min} \\ \frac{1}{v_{\max}-v_{\min}}(v_{\max} - \frac{L}{t}), & \text{when } L/v_{\max} \le t < L/v_{\min} \\ 0, & \text{when } t < L/v_{\max} \end{cases} \end{aligned} \tag{7.1}$$

where L is the cell size. Then, the pdf of T_i^{I} is given by

$$f_{T_i^{\mathrm{I}}}(t) = \begin{cases} \frac{L}{(v_{\max}-v_{\min})t^2}, & \text{when } L/v_{\max} < t \le L/v_{\min} \\ 0, & \text{otherwise.} \end{cases} \tag{7.2}$$

The handoff probabilities of MS u from its current cell o to its two neighboring cells, cell r and cell l are given by

$$\begin{aligned} p_{oru} &= L'/L, \\ p_{olu} &= 1 - L'/L, \end{aligned} \tag{7.3}$$

where L' is the distance between the current location of MS u and the left edge of cell o.

In the numerical results, the network is assumed to have 5 radio cells with cell size is $L = 1200$ m in length. The values of $v_{\min}$ and $v_{\max}$ are 5 m/s and 20 m/s, respectively.

7.2.2 Perfect power control case

The NCBP/HCDP's for voice, video and data traffic as a function of voice connection arrival rate are shown in Figs. 7.11-7.13. Throughout the numerical results, the unit of the connection arrival rate is number of connections per second. Resource utilization for each traffic class is shown in Figs. 7.14-7.16. Both analytical and simulation results are included in Figs. 7.11-7.14. The connection arrival intervals for both video and data connections are 10s. Each of the ϕ_i's is set to 0.8. The value of Δ^{p} is 10^{-4} for calculating the analytical results of NCBP. It can be seen that the analytical results match the simulation results quite well. Figs. 7.11-7.13 also show that NCBP/HCDP for each traffic class increases as the voice connection arrival rate increases. This demonstrates that the resource sharing effect in CDMA systems: increasing traffic load in one traffic class increases NCBP/HCDP of all the traffic classes in the system. From Figs. 7.11-7.13, it can be seen that voice connections receive better NCBP and HCDP performance than video and data connections because of the completely resource sharing policy used and because a voice connection requires much less than a video or data connection. The unfairness can be overcome by using partitioning-based approach, i.e., a certain amount of system resources is dedicated to serve a particular traffic class. However, the partitioning-based approach reduces resource utilization compared with the completely sharing approach [75].

Simulation results of resource utilization for different traffic vs. video connection arrival rate are shown in Figs. 7.14-7.16. As the voice connection arrival rate increases, resource utilization for voice connection increases significantly, while that for video and data traffic decreases very slightly. As the video connection arrival rate increases, resource utilization for video traffic increases significantly, and that for voice and data traffic decreases. Similarly, as the data connection arrival rate increases, resource utilization for data traffic increases significantly, and that for voice and video traffic decreases. Figs. 7.14-7.16 show that video and data traffic have greater impact on the NCBP/HCDP and resource utilization performance of each traffic class than voice traffic. The reason is that a voice connection requires much less system resource, including transmission rate and power, than a video or data connection.

Let $\phi_1 = \phi_2 = \phi_3 = \phi$. Figs. 7.17 and 7.18 show the effect of coefficient ϕ_i on the performance of the proposed RRM, where the new connection arrival interval is 10 s for each traffic class. From Fig. 7.17 it can be seen that increasing the coefficient decreases the HCDP for each traffic class, since more resource is reserved for handoff connections. It can also be seen from Fig. 7.18 that the resource utilization only decreases slightly by reserving resource for handoff connections. This demonstrates the effectiveness and the efficiency of the proposed RRM scheme.

Fig. 7.19 shows the performance comparison between the proposed joint RRM scheme and non-joint RRM schemes. Video traffic is used as the reference traffic. The non-joint RRM in Fig. 7.19 makes an admission decision for a video connection based on its peak transmission rate instead of the transmission rate as in (5.2). The average new connection arrival intervals for both voice and data traffic are fixed at 10 s. Coefficient $\phi_i = 0.8$ for each traffic class. From Fig. 7.19, it can be seen that the resource utilization for each traffic class in the joint RRM is higher than that in the non-joint RRM. This indicates that, by capturing the burstiness and randomness of the packet arrival process of the video connections through statistical multiplexing, not only the resource utilization for video traffic is improved, but also the resource utilization for voice and data traffic is improved. This also verifies the resource sharing effect in CDMA systems: efficient resource utilization within one traffic class improves resource utilization for the entire system. Fig. 7.19 also shows that the resource utilization improvement is more significant when the traffic load is higher, which indicates that the proposed RRM is especially desirable for high traffic load systems.

Figs. 7.20-7.23 show the advantage of resource reservation based on user mobility information in the proposed joint RRM scheme. Performance comparison is given between the proposed RRM scheme, referred to as partial reservation (PR) scheme, and two non-joint RRM schemes, respectively, which do not make use of the user mobility information. The two non-joint RRM scheme are full reservation (FR) and no reservation (NR). The difference between the two non-joint RRM schemes and the proposed scheme is that the FR scheme reserves 100% of resource for each connection in each of its neighboring cells, while the NR scheme does not reserve resources for handoff connections. In the simulation, the average new connection arrival interval is 10 s for voice and video traffic. The value of ϕ_i equals 0.8 for all i's in the proposed RRM scheme. From Figs. 7.20 and 7.21 it can be seen that, compared with the FR scheme, the proposed RRM scheme achieves both lower NCBP and higher resource utilization. Although the FR scheme can achieve zero HCDP, it unnecessarily wastes a lot of system resource, because no connection can be handed off the all the neighboring cells at the same time. In contrast, our proposed RRM scheme can achieve both low HCDP and relatively high resource utilization while achieving reasonably low HCDP ($10^{-5}-10^{-4}$). Fig. 7.21 also shows that the higher is the traffic load, the larger is the resource utilization improvement of the proposed RRM scheme over the FR scheme. The NR RRM treats handoff connections the same as the new connections and results in the same HCDP as NCBP, which is undesirable, especially at high traffic load. Fig. 7.22 shows that the proposed RRM scheme achieves much lower HCDP compared to the NR scheme. The reduced HCDP is obtained at the price of the reserved resources which result in reduced resource utilization. As is shown in Fig. 7.23, there is only a slight decrease in the resource utilization of the proposed RRM scheme compared with that of the NR scheme. Therefore, the proposed RRM scheme can achieve better trade-off between resource utilization and HCDP, and is more desirable than both the FR and NR schemes.

7.2.3 Imperfect power control case

Let the coefficient for resource reservation, ϕ_i, be 0.4. Figs. 7.24-7.32 show the simulation results of GOS performance under imperfect power control, where the standard deviation of power control errors under imperfect power control is 1 dB. It can be seen that the resource utilization under imperfect power control is less than that under perfect power control, and NCBP and HCDP under imperfect power control is larger than that under perfect power control. This shows that power control imperfection decreases the system GOS performance.

Fig. 7.24 shows that, as voice connection arrival rate increases (average interval decreases), resource utilization for voice traffic increases, while resource utilization for video and data traffic decreases slightly. Fig. 7.27 shows that, as voice connection arrival rate increases (average interval decreases), NCBP for voice traffic increases, while NCBP for video and data traffic increases slightly. Fig. 7.30 shows that, as voice connection arrival rate increases (average interval decreases), HCDP for voice traffic increases, while HCDP for video and data traffic increases slightly. Fig. 7.25 shows

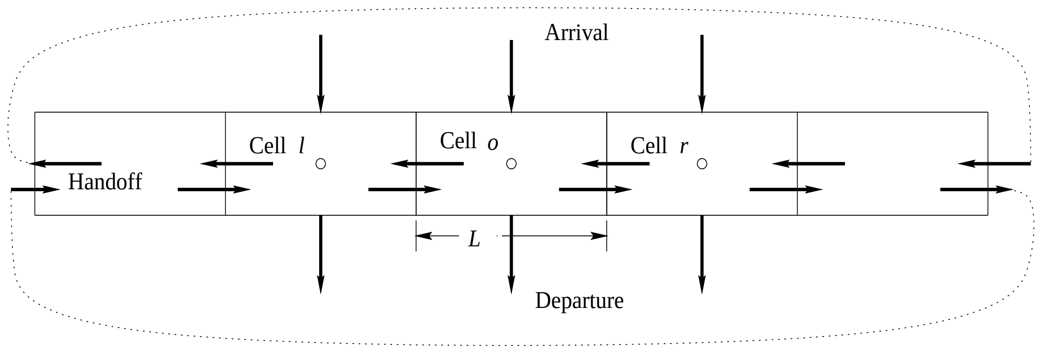

Figure 7.10: 1-D cell array

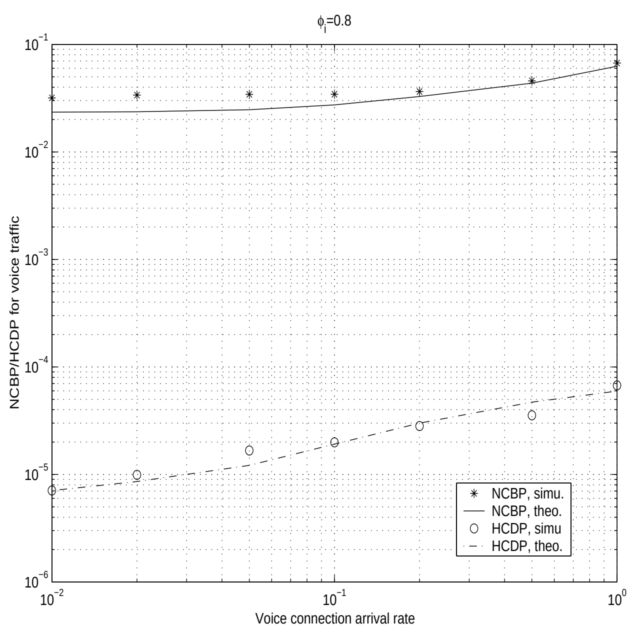

Figure 7.11: NCBP/HCDP vs. voice connection arrival rate: voice traffic

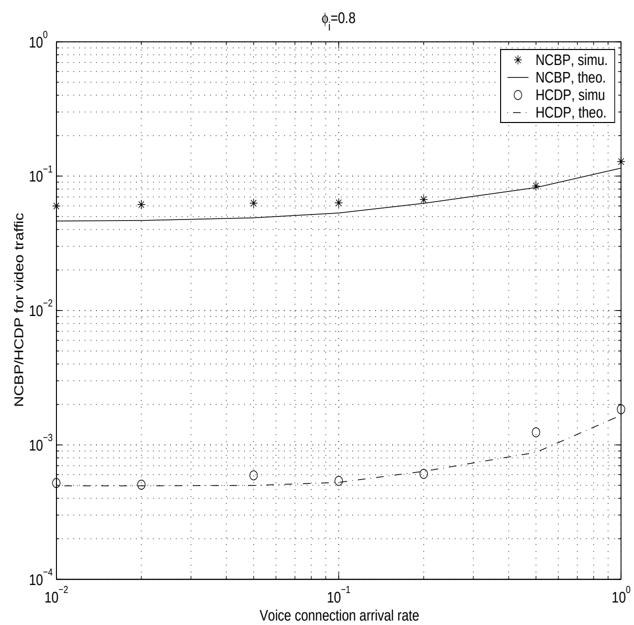

Figure 7.12: NCBP/HCDP vs. voice connection arrival rate: video traffic

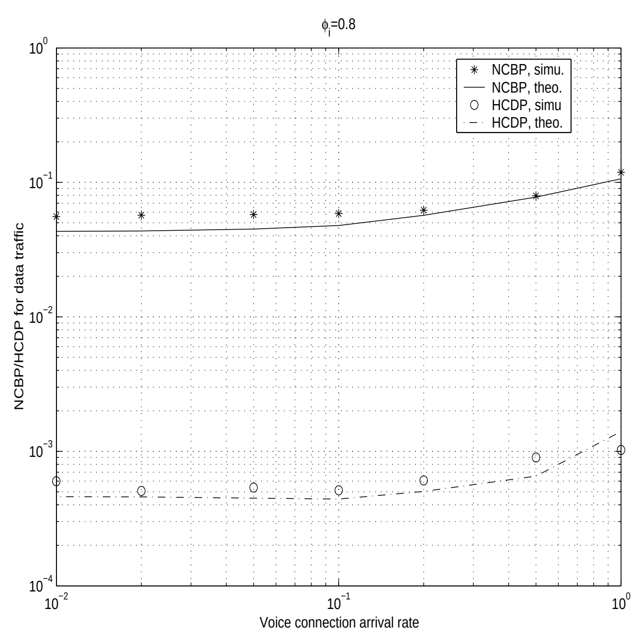

Figure 7.13: NCBP/HCDP vs. voice connection arrival rate: data traffic

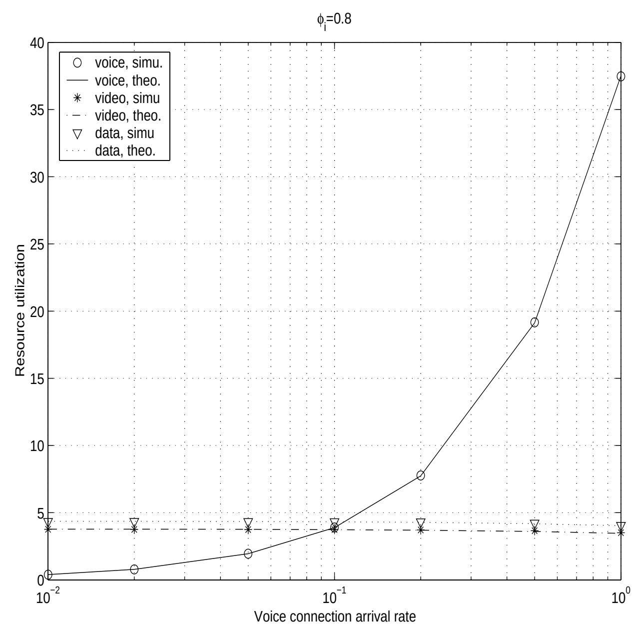

Figure 7.14: Resource utilization vs. voice connection arrival rate

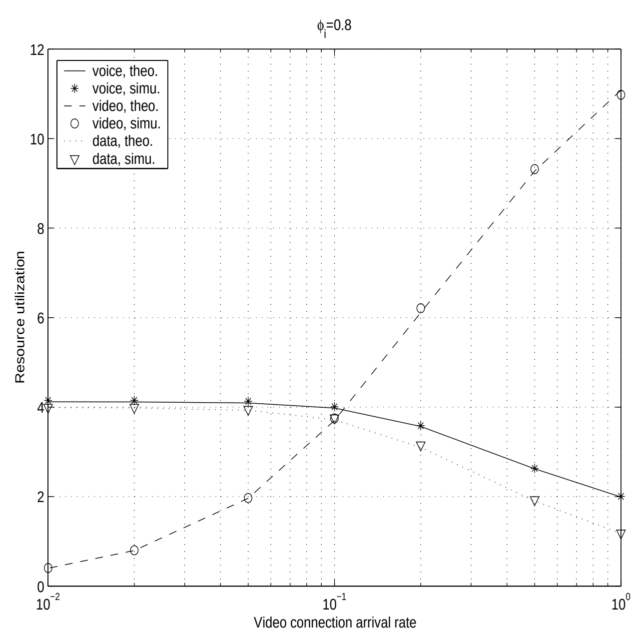

Figure 7.15: Resource utilization vs. video connection arrival rate

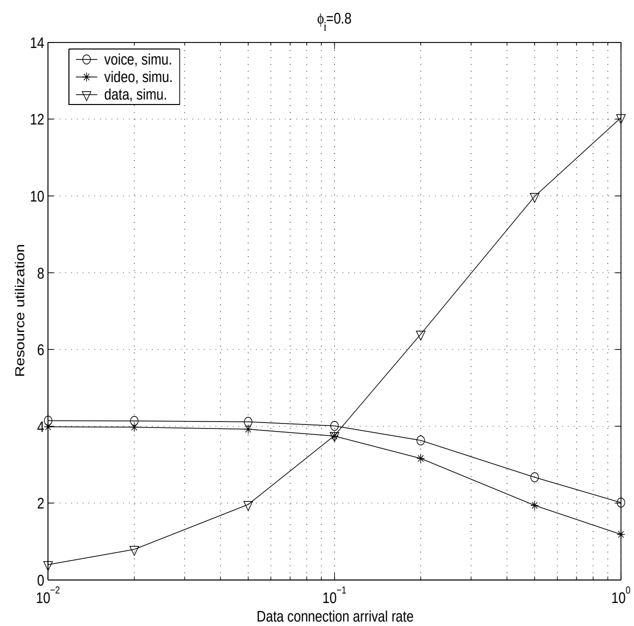

Figure 7.16: Resource utilization vs. data connection arrival rate

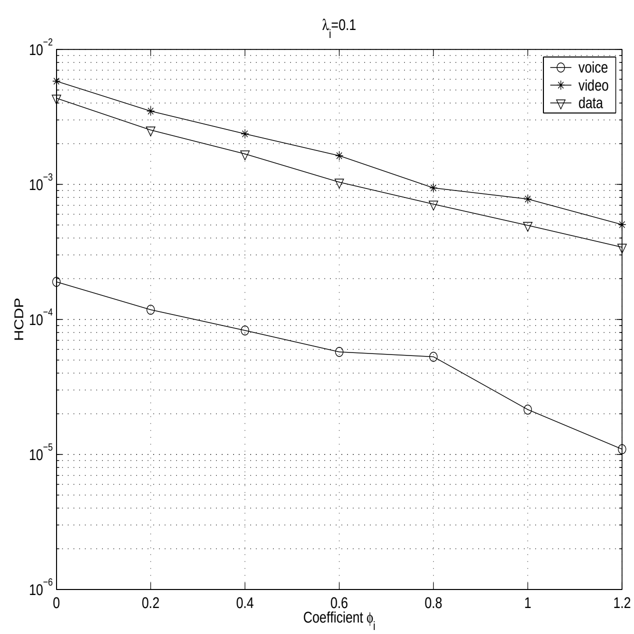

Figure 7.17: Effect of coefficient ϕ_i on HCDP

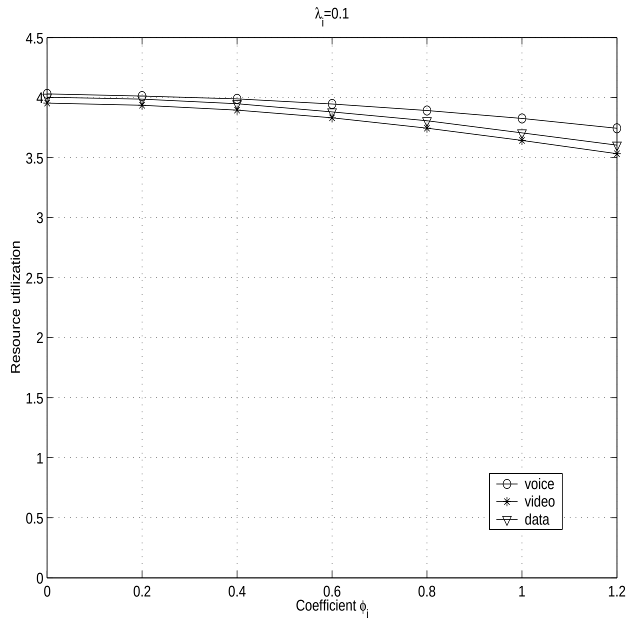

Figure 7.18: Effect of coefficient ϕ_i on resource utilization

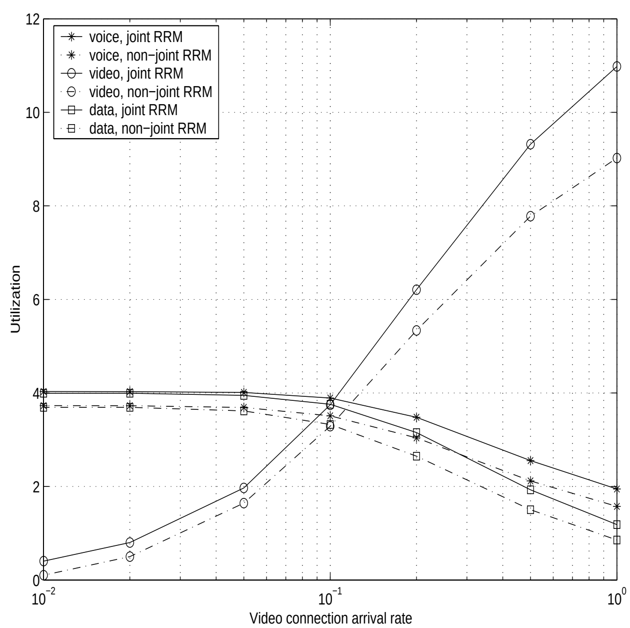

Figure 7.19: Resource utilization comparison between joint and non-joint RRM

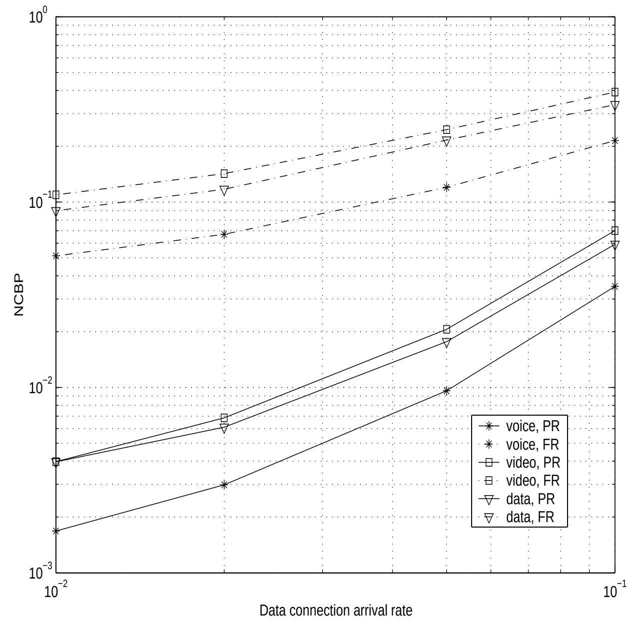

Figure 7.20: Comparison of NCBP between proposed RRM and FR RRM

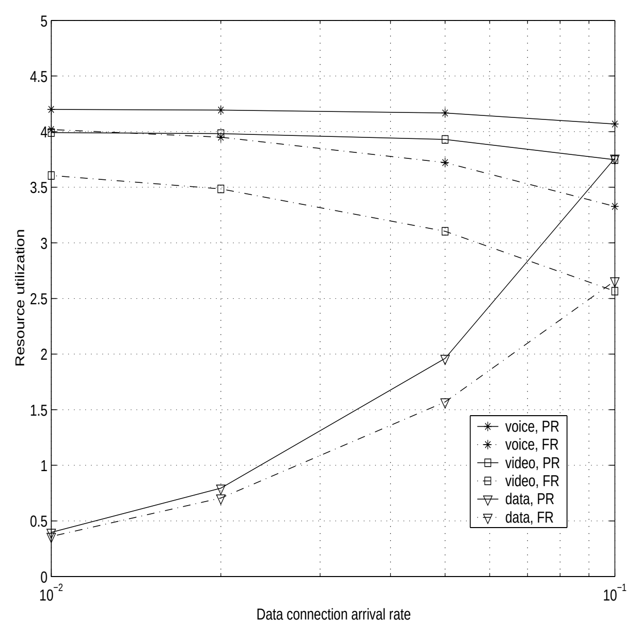

Figure 7.21: Comparison of resource utilization between proposed RRM and FR RRM

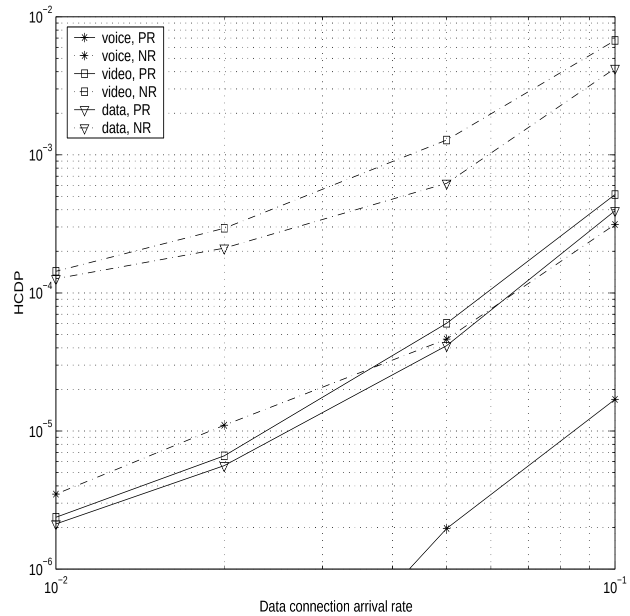

Figure 7.22: Comparison of HCDP between proposed RRM and NR RRM

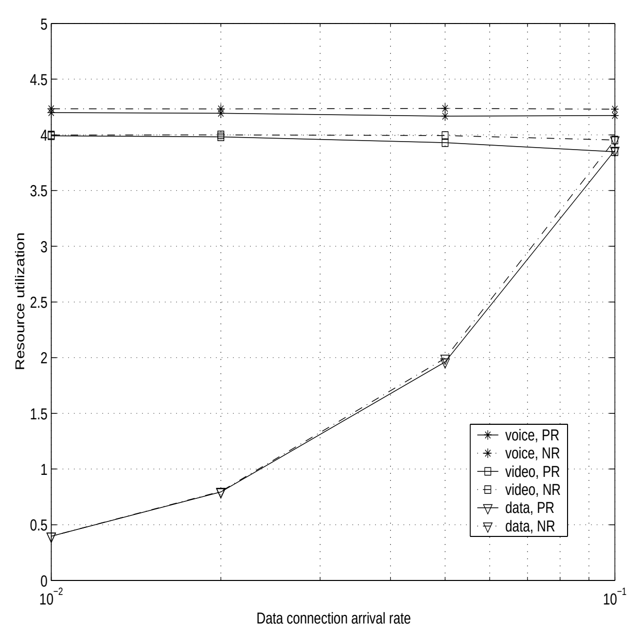

Figure 7.23: Comparison of resource utilization between proposed RRM and NR RRM

that, as video connection arrival rate increases (average interval decreases), resource utilization for video traffic increases, while resource utilization for voice and data traffic decreases significantly. Fig. 7.28 and 7.32 show that, as video connection arrival rate increases (average interval decreases), NCBP and HCDP for each traffic class increases significantly. Figs. 7.26, 7.29 and 7.32 show that data traffic change has the similar effect on the system performance as video traffic change does. In summary, similar to the perfect power control case, voice traffic change has less effect on the system performance than video or data traffic change.

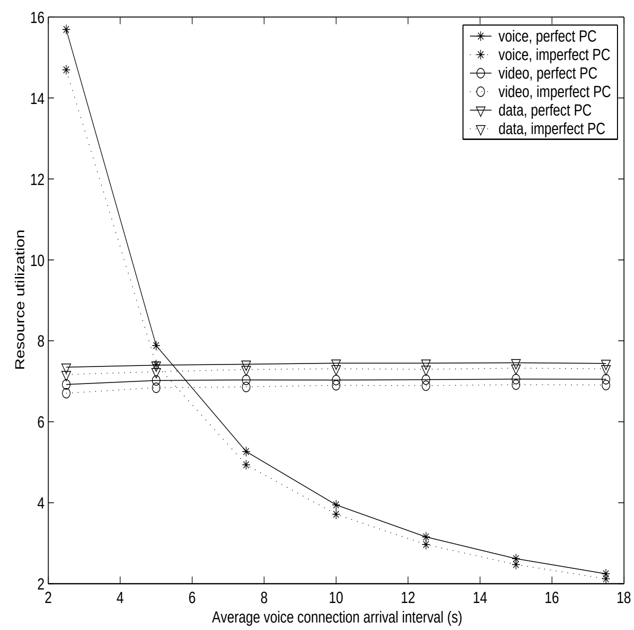

Figure 7.24: Resource utilization vs. average voice connection arrival interval

7.3 Summary

Numerical results have been presented to demonstrate the performance of connection level GOS performance of a single cell CDMA system and a cellular CDMA system,

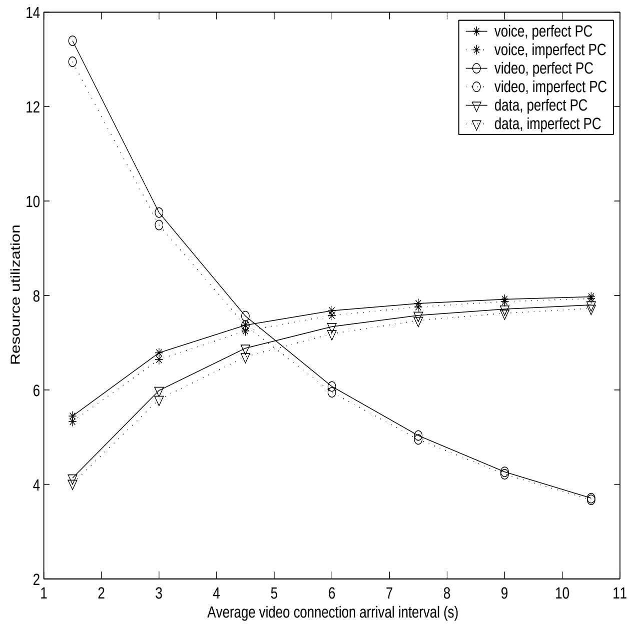

Figure 7.25: Resource utilization vs. average video connection arrival interval

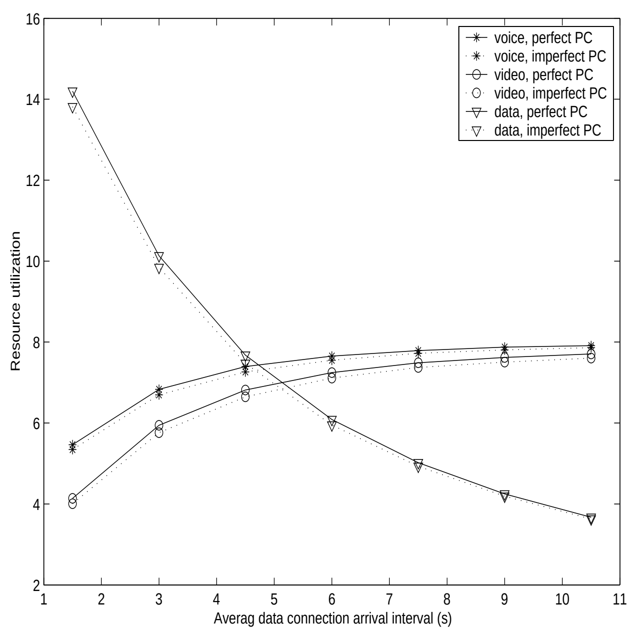

Figure 7.26: Resource utilization vs. average data connection arrival interval

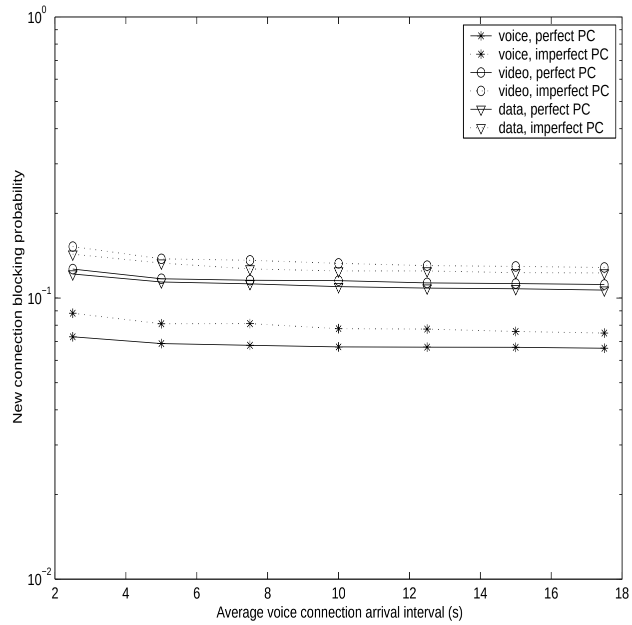

Figure 7.27: NCBP vs. average voice connection arrival interval

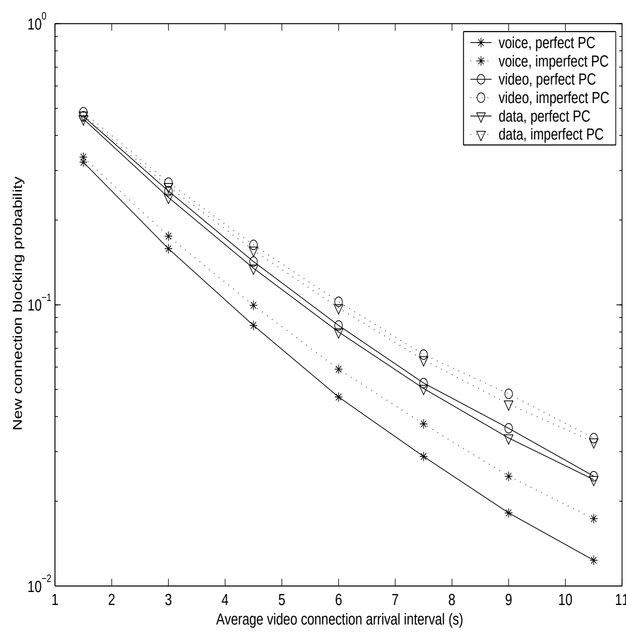

Figure 7.28: NCBP vs. average video connection arrival interval

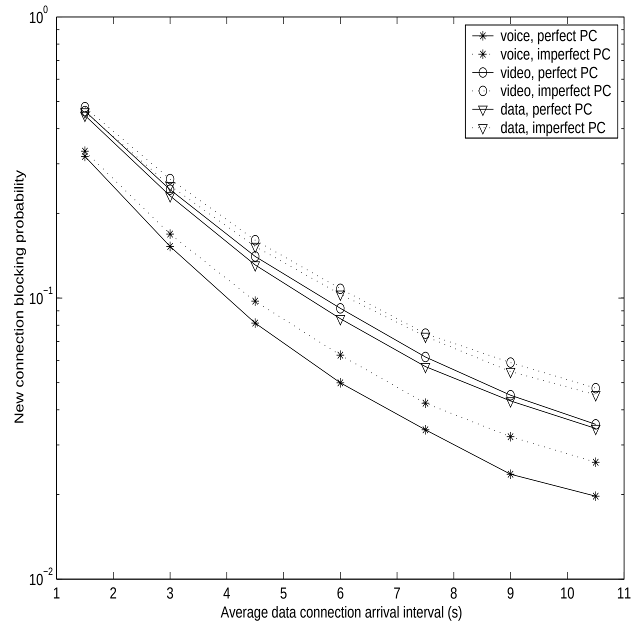

Figure 7.29: NCBP vs. average data connection arrival interval

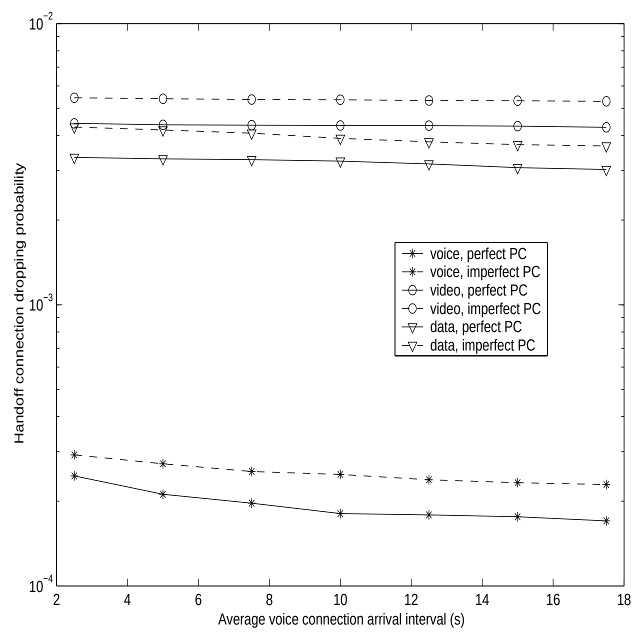

Figure 7.30: HCDP vs. average voice connection arrival interval

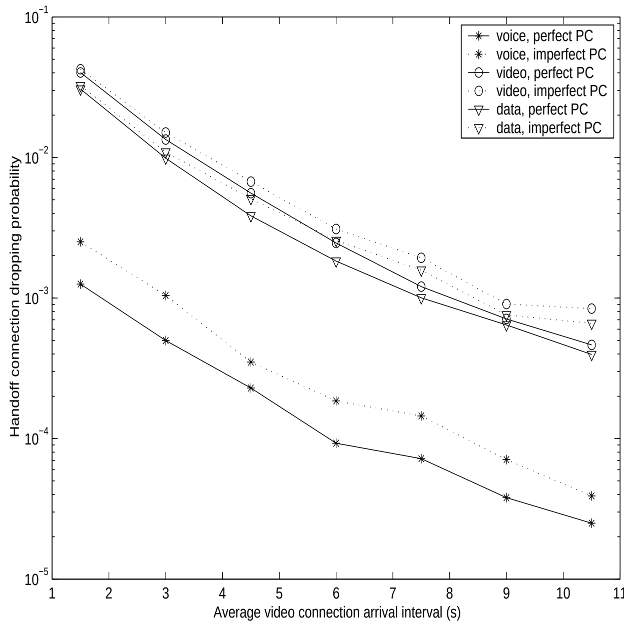

Figure 7.31: HCDP vs. average video connection arrival interval

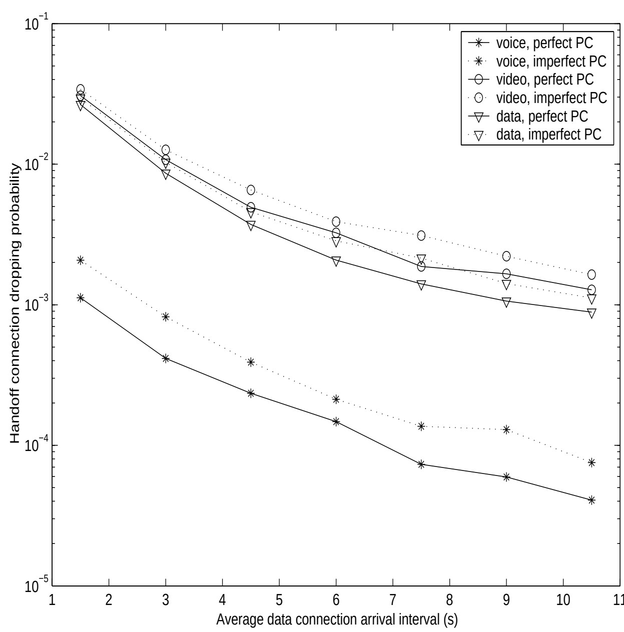

Figure 7.32: HCDP vs. average data connection arrival interval

under perfect and imperfect power control. The results show that:

- The GOS performance analysis in section 6.2 is verified by simulation results;
- Compared with other non-joint RRM schemes, the proposed joint RRM scheme can achieve low HCDP while keeping relatively high system resource utilization and low NCBP;
- Compared with the perfect power control case, power control imperfection results in reduction in resource utilization and increase in NCBP and HCDP;
- For cellular networks, resource reservation based on user mobility information can greatly reduce HCDP while keeping system resource utilization relatively high and NCBP relatively low;
- Due to the resource sharing effect, traffic change in one traffic class affects the GOS performance of all the traffic classes in the system;
- Voice traffic change has much less effect on the system GOS performance than video and data traffic because a voice connection requires much less system resource than a video or data connection.

Chapter 8

Conclusions and Future Work

8.1 Summary of contributions

A novel RRM scheme has been proposed in this thesis for cellular CDMA systems supporting heterogeneous services. The RRM scheme jointly takes the network characteristics at the physical layer, packet layer and networks layer into consideration. The scheme achieves effective and efficient radio resource utilization, which can benefit both the mobile users and the network service providers. The main contributions of this thesis are listed as follows.

- Effective and efficient power distribution has been derived for CDMA systems supporting heterogeneous services. The required SINR is guaranteed by distributing sufficient amount of power to each connection. By distributing only the necessary amount of power to each connection, maximum number of simultaneously transmitting users can be supported.

- Effective and efficient transmission rate allocation for heterogeneous traffic has been proposed. Delay/jitter and loss rate for different types of traffic is guaranteed. Statistically multiplexing the random and bursty traffic makes efficient utilization of the radio resource.

- A packet scheduling scheme for CDMA systems is developed. The scheme guarantees the required QoS for different traffic at a time slot basis, while maximizing the packet throughput for non-real-time traffic.

- A CAC scheme is proposed for cellular CDMA systems. The scheme ensures that once a connection is admitted into the system, its required QoS is satisfied throughout its connection lifetime. The CAC also makes resource reservation for potential handoff connections to achieve reduced HCDP. The amount of the reserved resource is based on user mobility information to achieve effective and efficient resource utilization.

- GOS performance for CDMA systems supporting heterogeneous services is derived, including NCBP, HCDP, and resource utilization.

- A fundamental understanding of the effect of power control imperfection is provided.

- A joint RRM scheme is proposed in this thesis. Specifically, it jointly considers radio channel condition and mobile user movement at the physical layer, packet scheduling through rate allocation and power distribution at the link layer, and connection admission control at the network layer. By taking the correlation among the network characteristics at the different layers into consideration, the RRM scheme can achieve guaranteed QoS performance at the packet level, and achieve better GOS performance at the connection level.

8.2 Concluding remarks

From all the work in this thesis, we can conclude that

- In heterogeneous CDMA systems, traffic change in each class affects the performance of all the classes in the system, because the available resource is shared by all the active users in the system. Therefore, improving the efficiency in resource allocation in one traffic class can improve the performance of all the traffic classes in the system.
- Due to the completely resource sharing policy, connections requiring less system resource always receive better GOS performance (in terms of NCBP and HCDP) than those requiring more system resources. In addition, fairness among different traffic classes (i.e., achieving the same level of NCBP and HCDP) may not be necessary if the amounts of required resources among them are significantly different. Because even a tiny amount of resource improvement for the class requiring a lot of resource would sacrifice the performance of the other traffic classes significantly.
- User mobility information is important for predicting the mobile users' movement and reserving resources for potential handoff requests.
- Power control imperfection increases the required power in order to achieve the same QoS and reduces the system resource utilization.
- The proposed CAC is for FDD/CDMA systems, but it can also be used in TDD based systems if perfect synchronization can be achieved in the entire system.
- Joint consideration of different network characteristics in the RRM in cellular

CDMA systems can achieve better resource utilization and effective QoS guarantee.

8.3 Future work

Future wireless communication systems will have higher capacity, provide higher data rate, more advanced services and flexible QoS guarantee, seamless handoff and user roaming.

As the Internet becomes increasingly popular, more mobile users get access to the Internet. For most users, the traffic downloaded from the Internet is much more than that uploaded to the Internet. The capacity of the downlink may become the restriction of the capacity of a CDMA system in the future. Therefore, it is important to study QoS provisioning and resource management for the downlink.

Handoff management is important for cellular communications. Currently, most of the handoff management schemes in the literature are for circuit-switched systems, and do not consider QoS guarantee. In future cellular communication systems, handoff management should take both packet level QoS and connection level GOS performance into consideration. How to maintain the correct sequence of the transmitted packets, reduce the experienced delay, and improve the packet throughput during the handoff are some important issues. Soft handoff is an important feature in CDMA systems to reduce the interference from users close the cell boundary. Research in this area may include the effect of soft handoff on the capacity improvement, QoS performance of the traffic in packet-switched systems, the HCDP by using various resource reservation strategies, etc.

At the same time as cellular wireless networks are growing rapidly, other air interfaces, such as Bluetooth and wireless LAN have also been developed and standardized. It is expected that cellular communications will play a major role in public mobile communication services, and wireless LANs will play a major role in private area communications. Short-range wireless systems will also be used to configure Personal Area Networks (PANs). When many types of networks can be used, users may wish to access each system according to the time, location, or other conditions. Therefore, interconnection between wireless access networks, and capability of handoff between wireless access networks will be of paramount importance. On the other hand, IP may potentially become the universal network-layer protocol over all wireless systems. The reasons are: 1) Because IP is a network protocol, it runs above the access network, and therefore is independent of the physical transmission medium and the access technology. 2) With multiple radio interfaces or software radio, a device could roam between different wireless systems if they all support IP as a common network layer. Moreover, IP is being improved to support voice. So, all traffic in mobile networks can be IP-based.

Research on resource management may also be extended to interconnected wireless and wireline systems, and to study the end-to-end performance of inter-connected wireline and wireless networks.

- QoS provisioning in the end-to-end environment

  In the inter-connected networks, a mobile station communicates with its serving base station via a wireless link, while the base station connects to wireline backbone networks through mobile switching center. An end-to-end connection may include hybrid wireless and wireline links. Effective and efficient QoS guarantee in the inter-connected networks requires much more complexity than the QoS provisioning in wireless access networks. The end-to-end QoS provisioning may have to map the end-to-end QoS into the QoS in each of the inter-connected links, and coordinate the QoS in the inter-connected links.

- Access control and admission control in the end-to-end environment

  QoS provisioning serves the basis for the access control and admission control research. In the inter-connected networks, the wireless segment is usually a bottleneck of the connections. Access control and admission control are of paramount importance in such networks. When considering access control and admission control in the end-to-end connections, not only the wireless access link should be taken into consideration, but also all the links in the connection.

- Mobility and handoff for interconnected wireless and wireline networks

  Due to small cell size for increasing the system capacity, cell dwelling time of users will be shortened and the handoff frequency will increase. Therefore, handoff management is more important in future wireless networks. Currently, most handoff schemes are for circuit-switched systems, and do not consider QoS support. In the inter-connected networks, when a mobile user moves between the areas of different MSCs, it may affect the end-to-end connections, e.g., how to re-establish an end-to-end connection and guarantee the required QoS during and after handoffs. Location management may become more important especially when the mobile users roam among different networks with different air interfaces.

Appendix A

BER Performance of Selected Coding Schemes

Consider a convolutional code of rate $R_c = 1/3$ and constraint length $M_c = 9$ with Viterbi decoding algorithm. The BER of a rate R_c convolutional code is bounded by [10]

$$P_b \leq \sum_{d=d_{free}}^{\infty} B_D P_d \tag{A.1}$$

where d_{free} is the free distance of the convolutional code, which can be found in [10] for given coding rate and constraint length. P_d is the probability of making an error when comparing two paths through the trellis whose codeword symbol sequences differ in d positions, and is given by

$$P_d \leq \frac{1}{2}\left(\frac{1}{1+SINR}\right)^d, \tag{A.2}$$

B_D is the number of input 1's in all the finite length codewords of Hamming weight d, and can be found in [112]. Based on these, the relationship between the BER performance and the SINR for the convolutional code of rate $R_c = 1/3$ and constraint

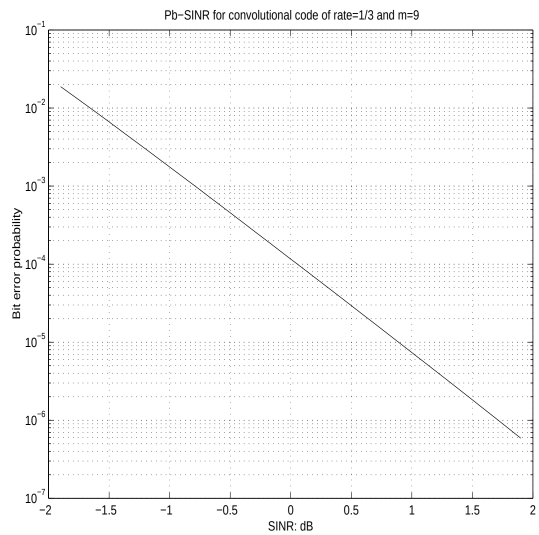

Figure A.1: BER vs. SINR for convolutional coding

length $M_c = 9$ is plotted in Fig. A.1.

Next, consider a concatenated coding scheme. The outer code is an RS code of $(16, 12, 5)$ (each symbol contains 5 bits, each codeword includes 16 symbols and 12 of them are information symbols), and the inner code is a convolutional code of $R_c = 1/2$ and $M_c = 9$. The BER performance for RS codes of (N, K, q) is given by [10]

$$P_{bc} < \frac{2^{K-1}}{2^K - 1} \sum_{j=t+1}^{N} \frac{j+t}{N} \binom{N}{j} P_s^j (1 - P_s)^{N-j} \tag{A.3}$$

where $t = \lfloor (N - K)/2 \rfloor$ is the error correction capability of the RS code, P_s is the channel symbol error probability and is bounded by

$$P_s \leq q P_b \tag{A.4}$$

for the concatenated code, and P_b is the BER of the inner codes and is given by(A.1). The BER performance for the concatenated code used in this research is shown in Fig. A.2.

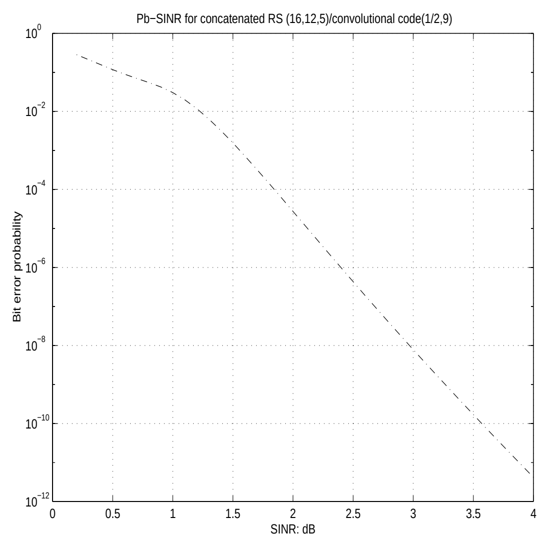

Figure A.2: BER vs. SINR for concatenated coding

Appendix B

Proof of Minimum Power

For S_j, $j = 1, 2, \ldots, k^{\mathrm{t}}$, given by (4.5), we have

$$\frac{3GS_j}{2(1+f)\sum_{n=1,n\neq j}^{k^{\mathrm{t}}} m_n S_n + 3GN_0 B_{\mathrm{b}}} = \gamma^*_{\theta_j}. \tag{B.1}$$

Rearranging (B.1) yields

$$2(1+f)\left(\sum_{n=1}^{k^{\mathrm{t}}} m_n S_n - m_j S_j\right) + 3GN_0 B_{\mathrm{b}} = \frac{3GS_j}{\gamma^*_{\theta j}}. \tag{B.2}$$

Suppose there is $\tilde{S}_l < S_l$, and $\tilde{S}_j = S_j$, for $j = 1, 2, \ldots, k^{\mathrm{t}}$ and $j \neq l$. We now prove that it is impossible to achieve $\gamma_l > \gamma^*_{\theta_l}$.

Proof. For received power $\tilde{S}_j$, $j = 1, 2, \ldots, k^{\mathrm{t}}$, the SINR at the BS receiver output for the lth connection is given by

$$\tilde{\gamma}_l = \frac{3G\tilde{S}_j}{2(1+f)\left(\sum_{n=1}^{k^{\mathrm{t}}} m_n \tilde{S}_n - m_l \tilde{S}_l\right) + 3GN_0 B_{\mathrm{b}}}, \tag{B.3}$$

which can be further rewritten as

$$\tilde{\gamma}_l = \frac{3G\tilde{S}_j}{2(1+f)\left(\sum_{n=1}^{k^{\mathrm{t}}} m_n S_n - m_l S_l\right) + 3GN_0 B_{\mathrm{b}}} \tag{B.4}$$

Combining (B.4) and (B.2) we have

$$\tilde{\gamma}_l = \frac{\tilde{S}_l}{S_l}\gamma^*_{\theta l}. \tag{B.5}$$

Since $\tilde{S}_l < S_l$, $\tilde{\gamma}_l < \gamma^*_{\theta l}$. This completes the proof.

Now we conclude that S_j, $j = 1, 2, \ldots, k^{\mathrm{t}}$, is the minimum power to achieve the required SINR for all the connections in the system.

Appendix C

Solving Equation Set (4.4)

First, repeat equation set (4.4) as follows:

$$\frac{3G + 2(1+f)m_i\gamma_i}{(1+f)\gamma_i}S_i - \sum_{j=1}^{K} 2k_j m_j S_j = \frac{3GN_0B_b}{(1+f)}. \tag{C.1}$$

Let

$$x_i = \frac{3G + 2(1+f)m_i\gamma_i}{(1+f)\gamma_i}. \tag{C.2}$$

(4.4) can be rewritten and extended as

$$\begin{cases} x_1S_1 - 2k_1m_1S_1 - 2k_2m_2S_2 - \cdots - 2k_Km_KS_K = \frac{3GN_0B_b}{(1+f)} \\ x_2S_2 - 2k_1m_1S_1 - 2k_2m_2S_2 - \cdots - 2k_Km_KS_K = \frac{3GN_0B_b}{(1+f)} \\ \cdots\cdots \\ x_KS_K - 2k_1m_1S_1 - 2k_2m_2S_2 - \cdots - 2k_Km_KS_K = \frac{3GN_0B_b}{(1+f)}. \end{cases} \tag{C.3}$$

Keeping the first equation unchanged and subtracting each of the following equations from the first one in (C.3) yields the following equation set:

$$\begin{cases} x_1S_1 - 2k_1m_1S_1 - 2k_2m_2S_2 - \cdots - 2k_Km_KS_K = \frac{3GN_0B_b}{(1+f)} \\ x_1S_1 - x_2S_2 = 0 \\ \cdots\cdots \\ x_1S_1 - x_KS_K = 0 \end{cases} \tag{C.4}$$

which can be further rewritten as

$$\begin{cases} x_1 S_1 - 2k_1 m_1 S_1 - 2k_2 m_2 S_2 - \cdots - 2k_K m_K S_K = \frac{3GN_0B_b}{(1+f)} \\ S_2 = \frac{x_1}{x_2} S_1 \\ \cdots\cdots \\ S_K = \frac{x_1}{x_K} S_1 \end{cases} \tag{C.5}$$

Substituting S_i, $i = 2, \cdots, K$, from the last $K-1$ equations in (C.5) to the first equation in (C.5) yields

$$x_1 S_1 - 2k_1 m_1 S_1 - 2k_2 m_2 \frac{x_1}{x_2} S_1 - \cdots - 2k_K m_K \frac{x_1}{x_K} S_1 = \frac{3GN_0B_b}{(1+f)} \tag{C.6}$$

Therefore, S_1 can be solved as

$$S_1 = \frac{3GN_0B_b}{(1+f)x_1\left(1 - \sum_{j=1}^{K} \frac{2k_j m_j}{x_j}\right)} \tag{C.7}$$

Substituting x_i as in (C.2) obtains S_1 as

$$S_1 = \frac{\frac{3GN_0B_b\gamma_1}{3G+2(1+f)m_1\gamma_1}}{1 - \sum_{j=1}^{K} \frac{2(1+f)k_j m_j \gamma_j}{3G+2(1+f)m_j\gamma_j}} \tag{C.8}$$

Then, S_i, $i = 2, \cdots, K$, can be solved as

$$\begin{aligned} S_i &= \frac{x_1}{x_i} S_1 \\ &= \frac{\frac{3G+2(1+f)m_1\gamma_1}{(1+f)\gamma_1}}{\frac{3G+2(1+f)m_i\gamma_i}{(1+f)\gamma_i}} \frac{\frac{3GN_0B_b\gamma_1}{3G+2(1+f)m_1\gamma_1}}{1 - \sum_{j=1}^{K} \frac{2(1+f)k_j m_j \gamma_j}{3G+2(1+f)m_j\gamma_j}} \\ &= \frac{\frac{3GN_0B_b\gamma_i}{3G+2(1+f)m_i\gamma_i}}{1 - \sum_{j=1}^{K} \frac{2(1+f)k_j m_j \gamma_j}{3G+2(1+f)m_j\gamma_j}} \end{aligned}$$

Appendix D

Moments of a Log-normally Distributed Random Variable

Let $\{Z_i\}_{i=1}^{K}$ be normal r.v.'s with mean and variance as $\mathrm{E}[Z_i] = \mu_z$, $\mathrm{Var}[Z_i] = \sigma_z^2$, respectively, and the correlation coefficient $\frac{\mathrm{E}[Z_i Z_j]}{\sqrt{(}\mathrm{Var}[Z_i]\mathrm{Var}[Z_j])} = \theta$ for $i \neq j$. Then, $Z_i + Z_j$ follows a normal distribution with mean $2\mu_z$ and variance $2(1+\theta)\sigma_z^2$. $e^{\beta Z_i}$ is a log-normal r.v., and its mean and variance can be calculated as:

$$
\begin{aligned}
\mathrm{E}[e^{\beta Z_i}] &= \int_{-\infty}^{\infty} e^{\beta x} \frac{1}{\sqrt{2\pi\sigma_z^2}} e^{-\frac{(x-\mu_z)^2}{2\sigma_z^2}} dx \\
&= \frac{1}{\sqrt{2\pi\sigma_z^2}} \int_{-\infty}^{\infty} e^{-\frac{(x-\mu_z+\beta\sigma_z^2)^2}{2\sigma_z^2}} e^{\frac{\beta^2\sigma_z^2+2\beta\mu_z}{2}} dx \\
&= e^{\frac{\beta^2\sigma_z^2+2\beta\mu_z}{2}} \frac{1}{\sqrt{2\pi\sigma_z^2}} \int_{-\infty}^{\infty} e^{-\frac{(x-\mu_z+\beta\sigma_z^2)^2}{2\sigma_z^2}} dx \\
&= e^{\frac{1}{2}\beta^2\sigma_z^2+\beta\mu_z} \qquad \text{(D.1)}
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{Var}[e^{\beta Z_i}] &= \mathrm{E}[(e^{\beta Z_i})^2] - (\mathrm{E}[e^{\beta Z_i}])^2 \\
&= e^{2\beta^2\sigma_z^2+2\beta\mu_z} - e^{\beta^2\sigma_z^2+2\beta\mu_z} \\
&= e^{\beta^2\sigma_z^2+2\beta\mu_z}(e^{\sigma_z^2\beta^2} - 1) \qquad \text{(D.2)}
\end{aligned}
$$

and the covariance

$$\begin{aligned}
\mathrm{Cov}[e^{\beta Z_i}, e^{\beta Z_j}] &= \mathrm{E}[e^{\beta Z_i} e^{\beta Z_j}] - \mathrm{E}[e^{\beta Z_i}]\mathrm{E}[e^{\beta Z_j}] \\
&= e^{(1+\theta)\beta^2\sigma_z^2 + 2\beta\mu} - e^{\beta^2\sigma_z^2 + 2\beta\mu} \\
&= e^{\beta^2\sigma_z^2 + 2\beta\mu}(e^{\theta\beta^2\sigma_z^2} - 1) \qquad \text{(D.3)}
\end{aligned}$$

for any $i \neq j$.

Appendix E

Proof of Existence of a Solution for p_i^{n}

A proof of the existence of a solution for p_i^{n} in the bisection algorithm in Section 6.2 for $K = 1$ is given in this appendix.

From (6.25) we have

$$\lambda^{\mathrm{h}} \approx \frac{\nu}{\mu}(1 - p^{\mathrm{n}})\lambda \tag{E.1}$$

Combining (6.19), (6.16) and (6.17) we have

$$p^{\mathrm{n}} = 1 - \frac{\sum_{k=1}^{N} \frac{1}{k!}\left(\frac{\lambda+\lambda^{\mathrm{h}}}{\mu+\nu}\right)^k}{\sum_{k=1}^{N} \frac{1}{k!}\left(\frac{\lambda+\lambda^{\mathrm{h}}}{\mu+\nu}\right)^k + \sum_{k=N+1}^{M} \frac{1}{k!}\left(\frac{\lambda^{\mathrm{h}}}{\mu+\nu}\right)^k}, \tag{E.2}$$

where M and N are the maximum number of the homogeneous connections and the maximum number of new connections that the system can accept, respectively. Replacing λ^{h} in (E.2) by (6.25) yields

$$p^{\mathrm{n}} = 1 - \frac{\sum_{k=1}^{N} \frac{1}{k!}\left[\frac{\lambda+\frac{\nu}{\mu}(1-p^{\mathrm{n}})\lambda}{\mu+\nu}\right]^k}{\sum_{k=1}^{N} \frac{1}{k!}\left[\frac{\lambda+\frac{\nu}{\mu}(1-p^{\mathrm{n}})\lambda}{\mu+\nu}\right]^k + \sum_{k=N+1}^{M} \frac{1}{k!}\left[\frac{\frac{\nu}{\mu}(1-p^{\mathrm{n}})\lambda}{\mu+\nu}\right]^k}. \tag{E.3}$$

Let $x = p^{\mathrm{n}}$. Finding p^{n} in the algorithm is equivalent to solving the following equation:

$$1 - z(x) - x = 0, \tag{E.4}$$

where $z(x)$ is given by

$$z(x) = \frac{\sum_{k=1}^{N} \frac{1}{k!} \left[\frac{\lambda + \frac{\nu}{\mu}(1-x)\lambda}{\mu+\nu}\right]^k}{\sum_{k=1}^{N} \frac{1}{k!} \left[\frac{\lambda + \frac{\nu}{\mu}(1-x)\lambda}{\mu+\nu}\right]^k + \sum_{k=N+1}^{M} \frac{1}{k!} \left[\frac{\frac{\nu}{\mu}(1-x)\lambda}{\mu+\nu}\right]^k}. \tag{E.5}$$

It can be seen that, $z(x) \in [0,1]$ is continuous. Because $0 < z(0), z(1) < 1$, $1 - z(0) - 0 > 0$, and $1 - z(1) - 1 < 0$, there must be $0 < x_0 < 1$, so that $1 - z(x_0) - x_0 = 0$. Therefore, there exists a solution of p^n.

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Author's Publications

A list of author's publications:

[1] D. Zhao, X. Shen and J. W. Mark, "Power Distribution and Connection Admission Control for a Multi-rate MC-CDMA System", submitted to *IEEE Transactions on Vehicular Technology.*

[2] D. Zhao, X. Shen and J. W. Mark, "Radio resource management for uplinks in cellular MC-CDMA systems supporting heterogeneous services", submitted to *IEEE Transactions on Wireless Communications.*

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