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CDMA Access to Multimedia Wireless PCS Systems

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the Faculty of Graduate Studies and Research
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Doctor of philosophy*

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Abstract

Radio resource management for multimedia CDMA wireless networks is the main focus of this thesis. We specialized on power management and call admission control due to their important roles in a comprehensive radio resource management scheme.

Bandwidth efficiency for a radio resource management technique is the most important requirement in a wireless medium with limited available bandwidth. In a CDMA cell with a mixture of different media with different quality of service requirements, efficient integration of traffic is a challenging task.

A novel joint access control and power assignment framework is proposed in this thesis. Power assignment algorithm provides the diverse required quality of services by the users through assigning appropriate amount of power to the users while access control monitors the number of users allowed in the cell in a way that guarantees the existence of a solution for the power assignment algorithm.

A call admission control scheme based on a modified equivalent bandwidth technique is proposed. On-line measurement of total interference at the base station is used to adjust the admission control policy.

We have shown that the proposed joint admission control and power assignment strategy is an effective method in providing guaranteed quality of service for real time multimedia traffic in an outdoor CDMA network.

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List of symbols

E_b	Transmitted energy per bit
E_b^*	Received energy per bit
$\widehat{E}_b$	Received energy per bit with imperfect power control
W	Total available bandwidth
R	Channel transmission bit rate
r	Source bit rate
$\bar{r}$	Average source bit rate
$\tilde{U}_i$	Activity ratio for source i
U_i	Activity ratio for source i after transmitter buffer
$\frac{S}{I}$	Signal to interference ratio
$\bar{\frac{S}{I}}$	Average signal to interference ratio
$\left(\frac{S}{I}\right)_{ij}^+$	Required average signal to interference ratio for the i^{th} mobile the j_{th} cell
$\left(\frac{S}{I}\right)_{ij}^*$	Required minimum signal to interference ratio for the i^{th} mobile in the j_{th} cell
β_i	The ratio of required minimum S/I to the require average S/I for the i^{th} mobile
σ_T^2	Back ground noise power
σ_k^2	Inter-cell interference power in the k^{th} cell
$\sigma_{(T)}^2$	Inter-cell interference power in a T unit time window

e	Equivalent bandwidth vector
α_j	Power increase ratio in the j^{th} cell
$\gamma_{opt,k}$	Optimum power coefficient in the i^{th} cell
$\alpha_{max,k}$	Maximum power increase ratio in the k^{th} cell
L_i	Outage probability threshold
$MRC(L)$	L^{th} percentile of interference power distribution
P_{ave}	Total average transmit power in the cell
$\tilde{\Pi}_i$	System outage probability under variable processing gain regime
Π_i	System outage probability under fixed processing gain regime
N_c, L	Total number of classes of traffic
M	Total number of cells in the network
h_{ij}	Path loss from the i^{th} mobile in the j^{th} cell to its home base station
$h_{ij}^{(k)}$	Path loss from the i^{th} mobile in the j^{th} cell to the base station in the k^{th} cell
$\widehat{h_{ij}^{(k)}}$	Ratio of path loss from mobile i in the j^{th} cell to the path loss from the same mobile to the k^{th} base station
$\mathbf{K}, \mathbf{N}$	Active user vector in the cell
ξ	A Gaussian random variable with zero average value
I_j	Total interference power in the j^{th} cell
π_{i1}, P_{i1}	Probability that the i^{th} user is active

Chapter 1

Introduction

The dissemination of heterogeneous information over a mix of fiber, cable, and wireless networks is progressing rapidly. A common heterogeneous network model will be wireless access to a high-speed wired core network.

During the last few years, there has been growing interest in cellular systems based on Code Division Multiple Access (CDMA). Recently, CDMA has been considered as a candidate for personal communication at 1.9 GHz in North America. High bandwidth utilization is one of the advantages of CDMA. The high bandwidth utilization is achieved by statistical multiplexing of independent signals which share the entire available bandwidth in the cell [17]. There are still many open questions that need to be answered before multimedia CDMA deployment. Radio resource management for wireless CDMA networks is among these open issues.

Quality of Service (QOS) provisioning for multimedia will prove critical for wireless networks. As wireless access to wired backbone networks grows increasingly, it becomes the bottleneck due to its severe resource constraints.

Low bandwidth and high error rates are among the many impairments that plague wireless networks and coupled with the time varying nature of the physical channel, they make the QOS contracts for heterogeneous applications difficult to promise with a high degree of certainty.

The QOS needs of the applications must ultimately be mapped onto the resources at the disposal of the wireless transport. These transport resources are

- (a) Link bandwidth;
- (b) Link buffering;
- (c) Power, or the strength of the transmit signal;
- (d) Signal processing for error control, e.g., forward error correction, channel equalization.

The allocation of link bandwidth and buffering is controlled by a multiplexer, which schedules the transmission of packets from various applications on a shared link and queues packets whenever traffic arrivals find the server busy. The allocation of power is

managed by a power control algorithm, which attempts to compensate for the time-varying impairments of the wireless media such as fading and noise. Careful allocation of power is particularly crucial for wireless cellular networks.

Lastly, the application of signal processing resources for error control is constrained partly by technology, such as limitations on hardware complexity and available portable battery power, and partly by the accompanying load that signal processing places on other transport resources (particularly bandwidth).

Considerably complicating resource allocation and making it an interesting problem is the fact that the mapping of a QOS component to a transport resource is not one-to-one correspondence. We may lower the loss rate of an application by giving its packets preferential treatment in the statistical multiplexer, thereby lowering the likelihood of stale or dropped packets; by increasing the transmit power level for the packet headers; by applying more redundancy in channel coding; or by any combination of the three strategies.

An application has some flexibility in trading off its rate, reliability, and delay needs against each other. For example, a video source may opt to forego compression and raise its bit rate requirements instead. The wireless network must attempt to allocate resources tailored to the needs of each individual QOS component of each application, where each QOS component may consume multiple resources.

We thus have a scenario where multiple QOS contracts, each with multiple components, are all competing for multiple network resources. The network must allow the applications to specify their needs in a flexible manner and, at the same time, deploy its limited resources efficiently so as to maximize system capacity.

In this thesis we specialized on the power assignment, and call and packet level control. The allocation of signal processing resources is beyond the scope of this thesis.

Power control is the adjustment of the transmit powers of user signals. It can substantially affect the capacity and perceived quality of service of cellular CDMA wireless systems.

The traditional power control law for a single rate traffic, which maintains the received energy per bit of all the users at a prescribed level, may no longer be applicable for multimedia networks.

In a multimedia scenario, both information rates and grade of service requirements for different classes of users vary considerably. In such systems, the power control scheme not only must mitigate the near-far problem but it should also balance the natural dissimilarity between the various classes of users.

Dissimilarities of services in a multimedia scenario introduce new challenges in power control design and power allocation plan.

Power control and power allocation are essential to the operation of multi-service CDMA networks. Power control is a mechanism that aims to keep the power at all the received signals at a preferred level while power allocation determines what the “preferred” level for each service is.

Proper power assignment can control the mutual interference among different services while keeping the required QOS of all services satisfied.

It is expected that the capacity limit will be reached in multimedia CDMA networks more often than in the existing networks, which are designed primarily for voice traffic. This limit is due largely to the presence of high bit rate and high power traffic in the mixture of multi-media traffic. In order to protect the quality of the existing connections in a cell from degrading below acceptable levels, call admission control is necessary in multimedia CDMA networks.

In this thesis we present our results on power assignment and admission policy in a CDMA integrated wireless access network.

1.1 Thesis summary

Retaining the attractive features of CDMA while providing QOS for different traffic streams, characterized by different QOS requirements is a challenging task for a radio resource management scheme [64]. Statistical variation in multimedia traffic, user mobility, strong interference from neighboring cells and imperfect power control are the issues that are to be taken into consideration in an efficient radio resource management design.

A non-linear power assignment algorithm is developed in this thesis. This algorithm takes into consideration both average and outage requirements of the bursty traffic [59][60]. The power control problem is formulated as a non-linear optimization problem, where the total

average power transmitted by the users is the objective function that should be minimized. Constraints are defined according to the average and outage requirements of the users.

The probability density function (PDF) of the signal to interference ratios experienced by the users have large variances in a multimedia CDMA scenario. This is mainly due to the large statistical variation in total traffic bit rate and due to the random changes in the power levels received from the mobiles at the base stations. Therefore, the quality of a communication link can not be satisfactorily characterized by its average signal to interference ratio (S/I) or outage probability alone [59].

We propose two performance indices to characterize the quality of a user's communication link, namely, average signal to interference ratio and outage probability. The outage probability is defined in the context of this work as the probability that the instantaneous S/I degrades below a predefined outage threshold.

An admission control algorithm is proposed in this thesis to regulate the access of new mobiles in the network. The combination of the proposed admission control and non-linear power assignment algorithm can provide the diverse quality of service required by different classes of traffic with a high level of reliability.

The proposed non-linear power assignment is an optimum technique in utilizing the cell capacity. However, due to the complexity that is inherent in this approach, an alternative method is explored in this thesis.

A joint power assignment algorithm and predictive call admission control are proposed that provide guaranteed QOS for the mobiles. In the proposed framework [55][56][57][58][61], a simple linear power assignment algorithm is developed that provides the diverse quality of services required by the users through assignment of appropriate amount of power to each user. Access control algorithm ensures the existence of a solution for the power assignment algorithm by limiting the number of users admitted in the cell.

Admission control, based on equivalent bandwidth technique, has been proposed for broadband ATM networks [13][31][42]. The main advantage of the equivalent bandwidth technique is its simplicity in conjunction with the efficient exploitation of statistical gain which is inherent in the statistical multiplexing of heterogeneous traffic.

There are several obstacles in employing the equivalent bandwidth methodology for access control in a wireless environment. The first problem is the fact that the equivalent bandwidth theory provides asymptotic results characterizing rare events and is suitable for a large capacity system. Such conditions may not be satisfied in a CDMA cell with limited capacity and moderate error rate. The second problem is the presence of significant inter-cell interference from adjacent cells and random fluctuations in the users' power levels inside a cell.

In this study we propose a new technique for access control in an outdoor CDMA cell supporting multimedia traffic [58]. The proposed scheme controls the flow of traffic at both packet and call level. Delay scheduling at packet level is employed to minimize the variance of intra-cell interference while a call admission control based on a modified equivalent bandwidth technique, which takes advantage of the minimized interference and reduces the call blocking probability.

In the proposed call admission control scheme, on-line measurement of total interference at the cell site is used to adjust the admission control policy. By comparing the predicted capacity derived from equivalent bandwidth technique and the one obtained from the interference measurement, the algorithm adaptively modifies the equivalent bandwidth control parameters according to a gradient descent algorithm.

1.2 Thesis outline

Since the characteristics of mobile channel impairment has a considerable impact on the system performance, some aspect of mobile communication and spread spectrum technique is discussed in the second chapter.

A detailed review of relevant published research is presented in Chapter 3. A summary of current standards and under development systems is also outlined in this chapter.

The system description and traffic models used in the simulation are discussed in Chapter 4. The issue of fixed versus variable processing gain transmission scheme for multimedia traffic is addressed. Some analytical and simulation results are provided to support the adoption of fixed processing gain scheme for the transmission of multimedia traffic in CDMA air interface.

An optimum non-linear power assignment algorithm is developed in this thesis and is introduced in Chapter 5. Analytical as well as simulation results are provided to highlight different aspects of the power assignment algorithm.

A sub-optimum linear power assignment is developed and is evaluated in Chapter 6. A novel two level access control strategy is proposed. This strategy, along with a linear power assignment algorithm, can provide guaranteed QOS for mobiles. Simulation and analytical methods are used to evaluate the performance of the proposed joint power assignment and admission control framework. The outcome of the evaluation is reported in Chapter 7.

The conclusions of this report are presented in Chapter 8.

Chapter 2

Spread spectrum and Mobile communication (Review)

In this chapter, we present background knowledge on the main aspects of spread spectrum techniques in mobile communication. Direct Sequence Code Division Multiple Access (DS-CDMA) is considered as the access scheme in this thesis. Advantages and limitations of DS-CDMA and other spread spectrum alternatives are outlined and compared.

2.1 Mobile communication environment

Introduction

Mobile cellular communication, like any other type of wireless communication, has the bandwidth limitation as its primary constraint. However, there are other important factors that significantly influence mobile communication performance and should be considered in any system design in the mobile environment.

Mobile channels exhibit different types of distortions. Frequency selective and flat fading, caused by delayed copies of the transmitted signal overlaying at the receiver, can reduce the signal amplitude and even cancel the signal completely. Shadowing, which is originated by propagation loss and terrain between base and mobiles, causes random attenuation in received signal envelope. User mobility creates another challenge by making the channel characteristics time variant and by creating Doppler phenomenon.

All the cells share the same frequency bandwidth under a standard Code Division Multiple Access (CDMA) scenario. Cell capacity is limited by co-channel interference in a CDMA cellular network.

In the next sections, these factors will be explained briefly.

2.1.1 Channel characteristics

If the receiver at the base station and the transmitters are located in an open field, then the transmitted wave travels through a single path to reach the receiver. However, in most cases the transmitted wave is reflected or diffracted by the objects that are located between the receiver and transmitter; consequently, the received signal at the cell site constitutes

several copies of the original signal. The radio channel impulse response, in its complex form, can be modeled by the following linear time-varying filter [82]:

$$h(t, \tau) = \sum_{k=0}^{N(\tau)-1} a_k(t) \cdot \delta(\tau - \tau_k(t)) \cdot e^{j\theta_k(t)} \quad \text{Eq(2.1)}$$

where t and τ are the observation time and application time of the impulses. $N(\tau)$ is the number of multi-path components. $\{a_k(t)\}, \{\tau_k(t)\}, \{\theta_k(t)\}$ are the random time varying amplitude, arrival-time, and phase sequences respectively. $\delta(\cdot)$ is the delta function.

The amplitude parameters in the impulse response are time variable due to the mobility of users or changes in some elements of surrounding environment. In other words, as the user moves from one place to another, it is likely to experience a different impulse response at different points in space. If the distance is comparable to the carrier wave length, user will experience small scale variations.

The small-scale fluctuations of the amplitude of the impulse response components, in absence of one strong component, are commonly modeled by Rayleigh distributions. For a cluster of Rayleigh scatterers, the probability density function (PDF) of the signal amplitude at the receiver is given by [82]

$$f_r(r) = \begin{cases} \frac{r}{\sigma^2} \cdot e^{-\frac{r^2}{2\sigma^2}} & r \geq 0 \\ 0 & r < 0 \end{cases} \quad \text{Eq(2.2)}$$

where r is the signal amplitude, and $\sigma^2 = \frac{1}{2}E\{r^2\}$ is the mean signal power.

In the case of a strong multi-path component, whether it is originated from the line of sight path or a path that goes through much less attenuation, the fluctuations has Rician distribution, as follows [97]

$$f_r(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{(r^2 + v^2)}{2\sigma^2}} \cdot I_0\left(\frac{rv}{\sigma^2}\right) & r \geq 0 \\ 0 & r < 0 \end{cases} \quad \text{Eq(2.3)}$$

where ν is non-centrality parameter, and $I_0(x)$ is zero order Bessel function.

The Nakagami-m distribution model is proposed when the received signal is accumulated from several Rayleigh fadings with arbitrary local-mean. The model is in the following form [97]

$$f_r(x) = \frac{2m^m \cdot x^{2m-1}}{\Gamma(m)\Omega_p^m} \exp\left\{-\frac{mx^2}{\Omega_p}\right\} \quad x \geq 0 \quad \text{Eq(2.4)}$$

where $x = r^2$ and r is the signal amplitude $\Omega_p = E[r^2]$, and $\Gamma(x)$ is the gamma function.

Mid-scale variation in received signal power, called shadowing, is due to the change of geometry of the reflectors in the mobile's environment. The shadowing phenomenon is approximated by the lognormal distribution, where its PDF is

$$f_r(r) = \begin{cases} \frac{1}{\sqrt{2\pi} \cdot \sigma_r \cdot r} e^{-\frac{(\ln(r) - \mu_r)^2}{2\sigma_r^2}} & r \geq 0 \\ 0 & r < 0 \end{cases} \quad \text{Eq(2.5)}$$

$R = \log(r)$ has Gaussian distribution with mean μ_r and variance σ_r^2 .

Third type of variation is due to the distance attenuation and typically is characterized by a d^{-n} factor, where d is the base-mobile distance, and n is a constant with typical value of 4.

2.2 Spread spectrum communication

Spread spectrum is a coding technique for digital transmission. The spread spectrum coder spreads out the signal spectrum so that the new spectrum has a significantly reduced power density, with the same total power. The expanded transmitter bandwidth minimizes interference to other users because of its low power density. In the receiver, the incoming signal is decoded and the decoding operation provides resistance to interference and multi-path fading.

There are two main variations of spread spectrum technique: frequency hopping and direct sequence.

2.2.1 Frequency hopping

In spread spectrum system based on frequency hopping, the carrier frequency of the transmitter changes (hops) in accordance with a pseudo-random code sequence. The order of frequencies selected by the transmitter is taken from a pre-determined set. The receiver tracks these changes and produces a replica of the desired signal. Interfering signals are not tracked. Therefore, they only occasionally fall within the IF bandwidth of the receiver.

Fast frequency hopping systems changes the carrier frequency at a significantly higher rate than the signal rate. Slow frequency hopping systems change frequency at a rate comparable with the signal rate.

2.2.2 Direct sequence

In direct sequence spread spectrum systems, the carrier phase of the transmitter, instead of the frequency, is varied according to a pseudo-random pattern. This pattern is generally achieved by multiplying the digital signal with a chip sequence. Since the chip sequence has a higher rate than the digital signal, the bandwidth is significantly expanded beyond the original information bandwidth. At the receiver, the information signal is recovered by multiplying it with a locally generated replica of the transmitted pseudo-random chip sequence. This effectively compresses the signal back to its original bandwidth. However, since interfering signals are subjected to only one multiplication process (in the receiver), the interference is spread at the receiver to at least to the bandwidth of the chip sequence. The spread interference can be removed by filtering.

For direct sequence, the amount of spreading is dependent on the ratio of chips per bit of information. The same chip sequence (or code) must be used in the transmitter and the receiver to recover the information.

Direct sequence is more popular than frequency hopping, due to the fact that frequency hopping requires a complex frequency synthesizer.

2.3 Spread spectrum and multiple-access

The spread spectrum technique can be employed in applications that require multiple access to network resources.

There are two main reasons for the use of spread spectrum as the multiple access scheme, namely, resistance to multi-path fading and greater capacity.

The main motivation for using CDMA in mobile radio is its resistance to multi-path fading. The received signal at the receiver is correlated with a signature sequence. Ideally, the signature sequence is completely random and thus has no correlation with a shifted version of itself. Therefore, if the excess delay is greater than one chip duration, the correlation with each of the multi-path components is zero. Effectively, this method will eliminate the multi-path.

When non-spread communications links are channelized, guard bands between channels must be allowed. Channels are prohibited from reuse within a minimal geographical distance. All these restrictions may theoretically be overcome by using a multiple access spread spectrum system. Spread spectrum systems may also improve efficiency when no interference protection is provided, for example with unlicensed use. In addition to these advantages when CDMA is used to transmit a bursty traffic, due to the statistical multiplexing, the capacity can be increased.

2.4 Mobile channel impairments and CDMA

While in narrow band channels, the multi-path propagation can cause deep fades and even signal cancellation (by equal delay and opposite phase path), spread spectrum signal experiences much more shallower fading, as explained in the previous section.

In a CDMA environment, with the use of a “RAKE” type receiver, the multiple paths can be demodulated individually, which will minimize the effect of interference and fading.

Closed loop power control is employed at the cell site in cellular CDMA to control other user interference and mitigate shadowing. In general, the effect of mobile channel impairment, especially shadowing, can be ignored if a perfect closed-loop power control is possible.

However, in a system with imperfect power control, there will be fluctuation at the user's received power around the target value, due primarily to shadowing and user mobility. This effect has been modeled by a lognormal variation in the user's power level [100].

2.5 The Near/Far problem and power control

Within a cellular system, on the reverse link, since signals originate from diverse and moving locations, they are not received at the same power by the base station. Signals

from users next to the cell site can overshadow the signals received from far distance. This problem is known as Near/Far problem.

This effect can be partially compensated for by power control, which takes two forms: open and closed loop power control. Under open loop power control, a mobile adjusts its power based on the strength of the signal it receives from the base stations. This method presumes that a reciprocal relationship exists between the forward and reverse links. This assumption may not hold if the links operate in different frequency bands. In a closed loop power control, the base station orders changes in the mobile transmitters based on the received power at the cell site.

2.6 Synchronization

Since CDMA works based on code multiplexing, one can expect synchronization to be one of the most important requirement of a functional CDMA system. In order to recover the desired signal, both the correlator and demodulator must be synchronous with the transmitted signal and be able to track it. The receiver should be able to lock on very quickly to the incoming signal from a cold start and should be able to keep the synchronization in the presence of interference.

Chapter 3

Current state of research and standards

A survey of the most notable published research on resource management and power assignment for multimedia CDMA is presented in the first section of this chapter.

An overview of the present standard and cellular systems that are under development is presented with greater emphasis on the CDMA based cellular network. The survey of the standard system shows the room for research contribution in developing a new standard for the third-generation cellular system.

3.1 Access control and power assignment in multimedia CDMA networks (literature review)

There are numerous published papers on the effectiveness of power control in fighting the near/far effect and increasing the cell capacity for homogeneous traffic [27][75][76]. Some of the papers in this group have focused on evaluating the performance of different methods of power control [2][110] while the others addressed the power control performance under different communication channel scenarios [14][100].

Power control/assignment for users with different bit rates and different required signal to interference ratios is addressed in [23][29][37][48][95][107]. The paper by Hanly [38] was the first paper that formulated the cell capacity region based on the required signal to interference ratios by the users. In another closely related paper by Hanly, a joint cell site and power assignment algorithm is introduced where the power assignment algorithm finds the set of transmission power values for the users that minimizes the total transmitted power over the entire network [32]. As part of the power control algorithm, the optimum cell site for each user is found; this optimum site minimizes the required transmit power. The idea of cell breathing, where the cell boundary is adapted dynamically according to the total interference at the base station is another contribution in Hanly's paper.

A comprehensive treatment of uplink power control in a CDMA cell, where users have different signal to interference ratio requirements, is presented in [107]. Convergence of the proposed power control algorithm under both distributed and central implementation is proved. In the centralized scheme, all the sites update the mobiles' powers simultaneously while in the distributed version, the mobile power level is updated independently. An

earlier theoretical work on convergence condition for a similar power control algorithm was reported in [23].

Using power assignment as an alternative to the variable rate coding for providing heterogeneous quality of service for the users was suggested in [51][106][109]. The problem of finding the optimum power levels that minimizes the transmitted power by the users, and consequently reduces the interference to the neighboring cells, has been formulated as a linear programming problem. It has been solved using a simple available linear programming algorithm [106].

The original power assignment algorithms developed by Yates [107] and Hanly [37] require perfect measurements of one or more of the following parameters:

- (a) channel gains of all the users,
- (b) the mobile's signal to interference ratio at the receiver,
- (c) the interference experienced by the mobiles,
- (d) the bit error rate.

However, these quantities are often difficult to measure.

In a paper by Ulukus and Yates [98], a stochastic approximation method is used to reduce the strong reliance of the power control algorithm on the above mentioned parameters. In their proposed power control algorithm, each user only needs to know its own channel gain to its assigned base station and its own matched filter output at its assigned base station. Convergence of their proposed distributed power control algorithm (in mean square error sense) to the minimum power solution has been proven mathematically.

In all the previously mentioned algorithms, the task of power assignment is based on providing a target signal to interference ratio for the users. Therefore, it is quite important to have a reliable method of calculating the target signal to interference ratio from the frame error rate. Assuming that perfect power control is realizable, the target signal to interference ratio can be calculated based simply on the coding gain of the coding scheme implemented in the frame. However, the problem becomes more complex when imperfect power control is considered. Some insight on this subject is provided in [94]. An adaptive method is proposed that adjusts the target required signal to interference ratio based on the measured frame error rate.

There are many publications that have dealt with bandwidth utilization in a CDMA network [26][27]. They focus on evaluating the system capacity under uniform and

homogeneous traffic conditions. The issue of admission control with heterogeneous traffic has not been addressed. In the work published by Khansari [47], a CDMA cell with a mixture of video and voice is considered. The effectiveness of a packet level control technique (ARQ) in providing the required service to both traffic types is investigated. However, they didn't address the call-level control mechanism.

Work reported in [53] probably is the first published research on admission control for multimedia CDMA. A combination of voice and data traffic is considered, but only deterministic traffic was considered (no statistical variation in source rate). A signal to interference ratio based admission control algorithm was developed that took into consideration the effect of other cell interference. Global knowledge of user attenuation to each cell site is assumed to be available at each base station. This assumption is highly unlikely to be realizable in a practical system.

A follow-up to the above research work was carried out by Dziong [17]. A call admission control algorithm based on signal to interference ratio is proposed that takes into consideration the effect of source traffic statistics. The probability density function of interference power is modeled by a Gaussian distribution. The parameters of the distribution is modified based on the traffic measurements.

An optimum policy for integration of voice and data is proposed in [33]. A semi-Markov decision process, with guaranteed bit error rate for voice and data traffic, is used to formulate the dynamic user admission. The proposed algorithm is excessively complex and is not suitable for real time admission control. In this work, inter-cell interference was not considered which, according to the paper, would result in even more complexity in the algorithm. In general, all the previously mentioned researches assumed that a perfect power control is realized and a more realistic imperfect power control scenario is not considered.

In a paper by Guo [25], an access control scheme for a CDMA cell with integrated voice and data traffic is proposed. In addition to the employment of ARQ for data traffic, a novel rate reduction scheme is proposed that minimizes the transmission delay among the data users by reducing the data traffic's bit rate and power. Pre-emptive priority was given to the voice traffic. The effect of inter-cell interference is accounted for in the access control scheme through a fixed interference coefficient. Power assignment is not addressed in this paper. The inter-cell interference coefficient was derived for the average interference level based on the assumption that the users' geometrical distribution was homogeneous in the

network. In a multimedia scenario, heterogeneous distribution of the users is a more realistic assumption.

A more complex algorithm on access control for data/voice CDMA was introduced in [89]. This work suggests time scheduling for data users to maximize the throughput of the data while the total interference on voice traffic is minimized. The proposed structure is a hybrid TDMA/CDMA where data users are separated in time and share the spectrum with the voice users based on a CDMA scheme. A similar scheme for real-time traffic is proposed in [58]. The integration of packet level and call level control is proposed in this paper.

User mobility and its impact on access control are important issues that need to be considered in the design process of an efficient admission control algorithm. The significant negative impact of a mobile user with bursty traffic on the CDMA cell capacity is addressed in [24][81].

In the work reported in [80][81], for a single type user (voice only), a simple adaptive threshold scheme for admitting the mobile user's is proposed. The admission threshold is modified adaptively according to the users' mobility. Extension of this work to the multimedia scenario is not straight forward.

Another recently published paper on the user mobility and access control is reported in [50]. In this paper, an algorithm is proposed based on the shadow cluster concept. Instead of a complete global knowledge of the attenuations to the cell sites, attenuation data is assumed to be known for a cluster of cells around the cell of interest (shadow cluster). The call admission control procedure requires the user mobility vectors for each user (direction, speed and location) from the shadow cluster cells to be known. Based on the mobility vectors, the system manager makes a statistically optimum decision that minimizes the call dropping probabilities by reserving some capacity in the cells for hand-off calls. Detailed mobility information, even from the cell of interest, is not readily available; and the problem is much more complicated for users in the neighboring cells. In this work, only single type of traffic is considered.

3.2 Present standards and future systems

In general, mobile communication systems can be classified into three categories:

- (a) Cellular systems,

- (b) Data systems,
- (c) Cordless telephone systems.

Cellular systems are designed primarily for supporting voice and low rate data. A cordless system is the wireless equivalent of the standard telephone. Wireless data systems are developed to support asynchronous packet switched communication.

Due to the relevancy to this thesis topic, existing and cellular systems that are under development are outlined in this section.

Cellular systems can be divided into three groups:

- (a) First generation cellular systems or analog cellular system,
- (b) Second generation cellular system or digital cellular systems,
- (c) Third generation cellular system (on going work).

3.2.1 Analog Cellular System

Frequency modulation (FM) is used for speech transmission and frequency shift keying (FSK) for signalling. Some example of systems that belong to this class of cellular system are: Advanced Mobile Phone Service (AMPS) in North America, Total Access Communication System (TACS), and RADIOcom 2000 in Europe and NIT in Japan. Frequency spectrum and number of channels are quite different in the above mentioned systems.

3.2.2 Digital cellular system

Digital cellular systems include the Global System for Mobile Communications (GSM) in Europe, IS-54 and IS-95 in the USA, and the Personal Digital Cellular (PDC) in Japan.

The IS-54 is based on the time division multiple access (TDMA) technique and supports three full-rate or six half-rate user slots on a single frequency channel of 30 KHz bandwidth. System capacity in the IS-54 is three times higher than in the system based on AMPS using the same spectrum.

The IS-54 system also provides services such as point-to-point short messaging, broadcast messaging, group addressing, and paging channels.

IS-95 is based on Code Division Multiple Access (CDMA). The basic user bit rate of 9.6

Kbps is spread to a channel chip rate of 1.22 Mcchips/sec. Two levels of spreading codes are employed. A long code, with a period of over one century, is used to create a large number of potential spreading codes—considering the fact that the number of unique codes in more common sets such as a m-sequence or Gold codes are too small. A short code is also used for spreading to enable convenient synchronization. Identical data is transmitted over I and Q channels using different short codes. Simultaneous transmission over the I and Q channel allows extremely sharp pulse shaping.

Data is encoded on the forward link using a rate 1/2 constraint length 9 convolutional code followed by an interleaver while a rate 1/3 constraint 9 convolutional code is used on the reverse link. On the reverse link, a Walsh code is used to modulate the data, providing another level of error correction.

On the forward link there is a sub-channel for power control purposes. Every 1.25 ms the base station receiver estimates the signal strength of the mobile unit, and consequently it issues the proper command to users to adjust their power level.

Both open-loop and closed-loop power control is used for tight control of the mobile's transmit power. Coherent detection is employed on the down link while non-coherent detection is used in the uplink. IS-95 has the advantage of increased capacity compared to IS-54 and flexibility to accommodate different rates.

3.2.3 Third generation cellular system

Third generation cellular systems represent future systems and are under development. Their objective is to provide sophisticated features and services, including multimedia communication. CODIT from the RACE project in Europe and ATDMA are the most important projects in this category.

CODIT is based on CDMA. CODIT supports a wide variety of traffics like VBR video and VBR speech and is part of the RACE project.

3.3 RACE project CDMA interface design

CDMA system with multiple RF channel bandwidths is proposed to implement an open and flexible radio interface, as required, for third-generation systems. In the CODIT project, an asynchronous direct-sequence CDMA technique with three different chip rates is implemented (1.023 and 5.115 and 20.46 Mcchips/s).

For every service, the parameters of the transmission scheme (coding rate, interleaving depth, chip rate, spreading factor, transmit power) can be adjusted to meet the specific requirements of the service to be provided.

The coding and spreading factor R_c/R_b , and hence the coding and spreading gain achieved in the proposed transmission scheme, varies with the information bit rate.

To support variable bit rate transmission in the proposed scheme, each CDMA frame is supplied with control information; variable bit rate transmission requires the provision of a control information specifying the instantaneous symbol rate. A frame length of 10 ms has been chosen. This frame length offers a sufficient degree of flexibility with respect to the data rate while the introduced transmission delay is kept to an amount that is considered to be tolerable for all expected services. The bit rate control information is transmitted on a separate physical channel.

3.3.1 Modulation

The basic modulation scheme used in the system is QPSK. The data symbols, fed to both in-phase and quadrature branches, are multiplied with different phases of the same long spreading sequence. If short spreading sequences are employed, two different PN sequences are used in the I and Q branches of the modulator. On the downlink, QPSK with coherent detection is employed. On the uplink, offset QPSK is used.

3.3.2 Power control

On the uplink, a combination of an open-loop and closed-loop power control is applied in order to keep the received signal power from the mobile station at a desired level at the base station. The open-loop power control is mainly used to track the shadowing and distance attenuation. The closed-loop power control tracks fading at low Doppler frequencies.

For the closed-loop power control, the base station constantly observes the received signal strength from mobiles. It determines the power control commands (transmitter power up or down requests) that are transmitted on a down link to the mobile station based on the measured signal power.

3.3.3 Soft hand-over and Macro diversity

To combat shadowing effects, soft hand over and macro diversity are used on the uplink. The signals sent out by a mobile station are simultaneously received by two or more spatially separated base stations. Diversity combining takes place at a common node in the hierarchically organized base station subsystem. This method may be implemented as a frame-by-frame selection combining. Diversity combining can also be implemented using an even more powerful method, maximum ratio combining, by using soft decoding information provided by the base station receivers.

On the downlink, two or more base stations may establish links and transmit the same information from different locations to a mobile station in soft hand-over. Maximum ratio diversity combining takes place in the rake receiver of the mobile station.

Mapping of user bit rates to chip rates in a CODIT environment

Chapter 4

System Description and Models

4.1 Introduction

The first section of this chapter describes the system architecture that is simulated in this thesis and outlines the underlying assumptions.

Simulation study of multimedia communication requires traffic models which preserve the main characteristics of the target sources. The second section of this chapter summarizes some of the traffic models suggested for multimedia communication in the literature and introduces models that are employed in this work.

There are several random processes, such as other cell interference and imperfect power control, that influence the quality of users' communication link in a multimedia CDMA wireless network. A system performance measure is introduced in this chapter that reflects the randomness in a communication link performance.

Both fixed and variable processing gain schemes for integrating multimedia traffic in a CDMA cell are proposed in the literature [4][51][87]. Under a fixed processing gain scheme, all the users transmit at a fixed channel transmission rate; users transmit at their original source rate under a variable processing gain scheme and consequently have different processing gains.

There hasn't been a clear criteria for choosing a fixed processing gain or variable processing gain scheme in the literature. These schemes are compared in terms of capacity utilization and complexity in the last section of this chapter. The fixed processing gain scheme has been adopted in this thesis as a result of this comparison.

4.2 Basic assumptions

The system under study in this thesis is an asynchronous cellular CDMA network with 16 equal size square cells, as shown in Figure 4.1. The total bandwidth shared by all the users using DS-CDMA signalling is assumed to be equal to 10 MHz. Cell size is considered to be 1.5x1.5 km.

Separate frequency bands are used for the reverse link and the forward link, in order that the mobiles only experience interference from the base stations in adjacent cells and the base stations only experience interference from the mobiles.

Base stations are located at the center of the cell. An omni directional antenna is used at the receiver. Each mobile is power controlled only by the base station of its home cell.

Three classes of real-time multimedia traffic are considered:

- (a) variable rate low bit rate video,
- (b) fixed bit rate video,
- (c) variable bit rate voice.

Call arrival process in a cell is modeled as independent Poisson process with a mean arrival rate of λ_k ($k=1,2,3$) for each class of traffic. Call duration is modeled as an exponentially distributed random variable.

It is assumed that users' terminals are equipped with output buffers that accumulate the generated data during a time window of "T", which is a design parameter. The buffered data is transmitted at the fixed rate of 144 Kb/s, which results in a processing gain of 69.4. A system diagram of a single cell with a fixed processing gain scheme is shown in Figure 4.2.

Figure 4.1: 16 cell Micro cellular system with square cells

Figure 4.2: Model of a single cell CDMA with fixed processing gain

4.3 Traffic models

The traffic models that are used in the simulation experiments in this thesis are explained briefly in this section.

Variable bit rate video

One of the main characteristics of VBR video is the relatively high correlation between consecutive arrivals of packets. A model for a video coder is considered to be efficient if it can accurately model the correlation that exists in video stream. There are two types of correlation in a video traffic stream: short and long term.

Short-term correlation is mainly related to small fluctuations in bit rates, and its effect lasts for a very short period of time (few hundred milli-seconds). Long-term correlation corresponds to sudden changes in the scene which create large changes in the rate of output stream and its effect last for a relatively long period of time (few seconds). There are a few models developed for VBR video modeling. One-dimensional multi-stage birth and death process with a fixed bit rate at each state is used to model the video encoder output bit rate [72]. In [84] a two dimensional Markov chain is proposed where one dimension corresponds to the short term correlation, and the second dimension with bigger jumps in bit rate, corresponds to the scene changes.

Transform-Expand-Sample or TES is another method used to model VBR video [70]. This model applies two random sequences to model the video stream. This technique effectively models the VBR video traffic, at the block and frame level.

ARMA (Auto-Regressive Moving Average) technique is another proposed method of modeling. These models generally fit the data well in a statistical sense and are basically used for simulations. In this thesis we used a simple model of this type, which is based on first order AR (auto-regressive) process with a Gaussian input [73][74]. This model is proposed based on the fact that the frame to frame bit-rate has a bell-shaped histogram that can be approximated by a Gaussian PDF.

Variable rate video source is modeled as an auto-regressive process with average rate of 32 Kb/s where instantaneous bit rate changes in the range of 0 to 128 Kb/s every 30 ms.

Voice model

A two state ON-OFF Markovian process is used to model the voice source output [7].

According to this model, a traffic source transmits at a fixed bit rate of R bits/s when it is active, and it is idle otherwise. The following parameters have been used in simulating a voice source traffic:

- (a) The constant bit rate in the ON-state (32 Kb/s),
- (b) The average time in the OFF-state (1.8s),
- (c) The average time in the ON-state (1.2s).

Fixed rate video

Fixed rate video is simulated as a 32 Kb/s fixed bit rate source.

4.4 Measure of quality of communication link

In this thesis, the performance of a communication link is characterized by a quality vector $\mathbf{Q}$ where $\mathbf{Q} = \left[\left(\frac{S}{I} \right)_{ave}, \left(\frac{S}{I} \right)_{min}, L \right]$. The first element of quality vector, $\left(\frac{S}{I} \right)_{ave}$, is the average signal to interference ratio, $\left(\frac{S}{I} \right)_{min}$ is the system outage threshold level for the instantaneous $\left(\frac{S}{I} \right)$ and L is the outage probability. Outage probability is defined as the probability that the instantaneous $\left(\frac{S}{I} \right)$ is below the threshold of $\left(\frac{S}{I} \right)_{min}$.

The $\mathbf{Q}$ vector is chosen as the performance index for a communication link in this thesis based on the following observations. To the system manager, the S/I at time “t” or S/I(t) is the most convenient information to analyze among the information available at the cell site. This observation is due to the fact that the total interference power is a superposition of the interferences caused by each connection signal. The effect of a new user on the cell interference power level can be evaluated by adding the predicted interference power from the new call to the existing total interference power. This is very important from the point of view of radio resource management.

Another reason to choose (S/I) as the performance measure is based on the fact that there is a one to one correspondence between the bit error rate and S/I. There is a direct relation between (S/I) and the bit error rate in the un-coded channel $BER_{uncoded}$ and between $BER_{uncoded}$ and bit error rate after decoding of the stream of the received code symbols BER_{coded} [17].

Furthermore, due to the large statistical variation in a link’s signal to interference ratio in a multimedia scenario, the average S/I alone is not a representative performance index. The combination of outage probability and average S/I can characterize the link quality more accurately.

Table 4.1 contains a set of required average cell error rates by typical multimedia services [71]. Typical Q-vector for the three classes of traffic considered in this work can be calculated based on the data from this table, the coding gain of the coding scheme, and the receiver's structure.

Table 4.1: Requirements of typical multimedia services [22][71]

Service type		Bursti- ness	Burst duration	Required bandwidth	Maximum cell loss	Maximum transmission delay
Real Time	VBR (CBR) Voice	5-15	1 sec	16-256 Kbps	10^{-3} - 10^{-6}	150-250 ms
	VBR(CBR) Video Telephony	2-5	30-100 ms	64 Kbps	10^{-4} - 10^{-6}	150-350 ms
	VBR(CBR) VIDEO Conferencing	2-5	30-100 ms	64-320 Kbps	10^{-4} - 10^{-6}	150-350ms
	VBR (CBR) MPEG Video	2-5	33 ms	1-4 Mbps	10^{-4} - 10^{-6}	40 ms
	VBR(CBR) HDTV VIDEO	2-5	33 ms	20-150 Mbps	10^{-4} - 10^{-6}	40 ms
Non-Real Time	File Transfer Electronic Mail	1	1 sec	9.6 Kbps- 9Mbps	10^{-9}	10-100sec
	Medical X-ray Still Image	25	1 sec	1-10 Mbps	10^{-9} - 10^{-12}	1-5 sec
	Document Retrieval Data on demand	40-200	40-250 ms	64 Kbps 5 Mbps	10^{-9} - 10^{-12}	1-3 sec

4.5 Calculating S/I in a CDMA cell

Statistical modeling of intra-cell interference has been investigated by many researchers [62][66][79][79][92][105]. A general expression for interference power, which is derived in [92][93], has been widely accepted. It is shown that the variance of intra-cell interference can be calculated as:

$$\text{var}(I(t)) = \beta \sum_{i=1}^{K(t)} \alpha_i(t) [(\Delta_i^2 + (1 - \Delta_i)^2) (\cos(\theta_i))^2] \quad \text{Eq(4.1)}$$

where $\beta = G \cdot P_0(t)$, G is the processing gain, and $P_0(t)$ is the desired user power level at time t . Furthermore, $\alpha_i(t) = \frac{P_i(t)}{P_0(t)}$ where $P_i(t)$ is the user i power level, and $K(t)$ is the number of users at time t .

θ_i and Δ_i are the carrier and chip phases of the i^{th} signal with respect to the desired signal.

The data sequence and the spreading code sequence both take the values of $\{-1, 1\}$ with equal probability. The carrier phase is assumed to be uniformly distributed in the interval of $[-\pi, \pi]$, and the chip phase is assumed to be uniformly distributed in $[0, 1]$. Details of the derivation can be found in Appendix B or [92].

It is assumed that a correlator receiver is used at the base station, and a random long code is assigned to each user. Modulation technique employed at the transmitter is assumed to be binary phase shift keying. Self interference, caused by the multi-path components of the desired signal, is assumed to be negligible.

At the network level, it is desirable to characterize the performance of a communication link using a small set of parameters. The general expression in Eq(4.1) for interference variance is difficult to compute due to the large number of parameters which are not readily available at the base station.

White Gaussian approximation for the interference was proposed in [105]. Under this assumption, the interference variance can be calculated for a fixed processing gain scheme as

$$\text{var}(I(t)) = \left(\frac{R}{W} \cdot \sum_{i=1}^N P_i(t) \right) \quad \text{Eq(4.2)}$$

where R and W are the channel transmission bit rate and total available bandwidth in the cell respectively.

S/I at time t , based on white Gaussian approximation can be found as

$$\frac{S}{I}(t) = \frac{P_o(t)}{\left(\frac{R}{W} \cdot \sum_{i=1}^N P_i(t) \right)} \quad \text{Eq(4.3)}$$

White Gaussian approximation for the intra-cell interference power provides an upper bound for the variance of interference derived from Eq(4.1). Therefore, it is a suitable performance measure for a call admission control scheme.

It is worth mentioning, that although the instantaneous interference is modeled as a Gaussian random variable, the distribution of total received power ($\sum_{i=1}^N P_i(t)$) is not necessarily Gaussian. This point will be explained further in Chapter 7.

4.6 Comparison between fixed and variable processing gain schemes

In the proposed architecture, all the transmission rates are mapped to 144 Kb/s. A similar bursty scheme was originally proposed in [87]. Another alternative is to allow users to transmit at their source bit rate, and therefore a different processing gain would be achieved for different users.

The main advantage of the fixed processing gain scheme over the variable processing gain scheme is its simplicity. The fixed processing gain scheme can accommodate other services as long as its data rate requirements are less than the fixed system transmission rate. Therefore, this scheme has the potential to integrate many other services by a uniform air interface. Furthermore, supporting variable rate traffic by the variable processing gain scheme requires an additional physical channel for transmitting the value of instantaneous bit rate to the receiver.

A higher peak to average power ratio is the main disadvantage of the fixed processing scheme, due to the transmission at high bit rate.

Presence of silence periods in the fixed processing gain scheme could make the synchronization process rather complex. However, this problem can be avoided by transmitting low bit rate and low power synchronization data during the silence period.

4.6.1 Comparing the Q-vectors for fixed and variable processing gain schemes

It can easily be proven that for a given energy per bit, users will have similar average signal to interference ratios under both schemes. The focus of this section is on comparing the overload or outage probability measured at the receiver when these two transmission schemes are used.

Outage probability for single and multi class ON-OFF sources under two spreading schemes are compared analytically. The operating region for each scheme where it has lower outage probability than the other technique is determined numerically. For the mixture of fixed and variable rate video and voice where analytical method was not possible, simulation is used to compare the overload probability under the two spreading schemes. Simulation extended the results from analysis to more general types of traffic.

Cell with a single class of ON-OFF Markovian sources

A single cell with N identical ON-OFF Markovian sources is considered. Denoted by $f(\tilde{U}_i)$ the probability distribution of activity ratio of the i^{th} mobile in the cell

$$f(\tilde{U}_i) = \begin{cases} \tilde{P}_1 & \text{if } \tilde{U}_i = 1 \\ \tilde{P}_0 & \text{if } \tilde{U}_i = 0 \end{cases} \quad \text{Eq(4.4)}$$

Source transmission rate at ON state is assumed to be r . Furthermore, denoted by E^*_{bi} and $\left(\frac{S}{I}\right)^*$, the received energy per bit from the i^{th} mobile at the base station and the minimum required signal to interference ratio for each user respectively. E^*_{bi} is assumed to be the same under the fixed and variable processing gain schemes.

Assuming perfect power control and negligible background noise, the outage probability for user i under the variable processing gain regime can be calculated as

$$Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)^*\right) = prob\left(\frac{E^*_b \cdot r \cdot \tilde{U}_i}{N} \leq \left(\frac{S}{I}\right)^*\right) \quad \text{Eq(4.5)}$$

$$\frac{r}{W} \sum_{m=1}^N E^*_b \cdot r \cdot \tilde{U}_m$$

E_b^* is the common received energy per bit from the mobiles. Since perfect power control is assumed, received energy per bit for mobiles are equal $E_{b1}^* = \dots = E_{bN}^* = E_b^*$.

The expression for outage probability under variable processing gain scheme can be further simplified by using the total probability law

$$\begin{aligned} \text{prob}(\text{overload}) &= \tilde{P}_1 \cdot \sum_{k \in S} \binom{N}{k} (\tilde{P}_1)^k \cdot (1 - \tilde{P}_1)^{N-k} \\ S: \{k\} \text{ where } k \left(\frac{S}{I}\right)^* &\geq \frac{W}{r} \end{aligned} \quad \text{Eq(4.6)}$$

Equation (4.6) is derived based on the assumption that the total interference power has a binomial distribution. This assumption is well justified due to the fact that each traffic source is modeled by an ON-OFF Markovian model.

Outage probability for the fixed processing gain scheme can be derived in a similar manner to the variable processing gain scheme as

$$\text{Prob}\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)^*\right) = \text{prob}\left(\frac{E_b^* \cdot R \cdot U_i}{\frac{R}{W} \sum_{m=1}^N E_b^* \cdot R \cdot U_m} \leq \left(\frac{S}{I}\right)^*\right) \quad \text{Eq(4.7)}$$

In Eq(4.7), R is the system's fixed transmission bit rate and random variable U_i is the activity ratio of traffic sources after the transmitter's buffer in the fixed processing gain transmission scheme.

The probability distribution function of U_i can be derived from the probability distribution of $\tilde{U}_i$ as

$$f(U_i) = \begin{cases} P_1 & \text{if } U_i = 1 \\ P_0 & \text{if } U_i = 0 \end{cases} \quad \text{Eq(4.8)}$$

P_1 is calculated using a simple intuition as $P_1 = \tilde{P}_1 \cdot \frac{r}{R}$.

The expression for outage probability under fixed processing gain scheme can be further simplified by using the total probability law as

$$Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)^*\right) = Prob(U_i = 1) \cdot prob\left(E^*_b \cdot R \left(\frac{R}{W} \sum_{m=1}^N E^*_b \cdot R \cdot U_m\right)^{-1} \leq \left(\frac{S}{I}\right)^*\right)$$

OR

Eq(4.9)

$$Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)^*\right) = Prob(U_i = 1) \cdot prob\left(\left[\sum_{m=1}^N \left(\frac{S}{I}\right)^* U_m\right] \geq \frac{W}{R}\right)$$

A closed form expression for the outage probability can be found as

$$prob(overload) = P_1 \cdot \sum_{k \in S} \binom{N}{k} (P_1)^k \cdot (1 - P_1)^{N-k}$$

Eq(4.10)

$$S: \{k\} \text{ where } k \left(\frac{S}{I}\right)^* \geq \frac{W}{R}$$

By comparing the expressions for the outage probability under the two transmission schemes and by noticing that

$$P_1 \ll \tilde{P}_1 \quad \text{while} \quad \frac{W}{r} \gg \frac{W}{R}$$

Eq(4.11)

One can expect that, for the large number of users, the overload probability will be smaller under the fixed processing regime than under the variable processing gain scheme while the opposite is true for small number of users.

The outage probability for both schemes is compared numerically for several minimum required signal to interference ratios $\left(\frac{S}{I}\right)^*$. Results are shown in Fig(4.3). Numerical results confirm our statement in the previous paragraph.

Cell with multi- classes of ON-OFF Markovian sources

In this section, outage probability expressions in Eq(4.8) and Eq(4.10) are extended to the case of several classes of ON-OFF Markovian sources.

Assuming L classes of traffic and N_n users from each class ($1 \leq n \leq L$), outage probability for a user from class i ($1 \leq i \leq L$) under the fixed processing gain scheme can be derived as

$$\Pi_i = Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)^*\right) = Prob(U_i = 1) \cdot prob\left(\sum_{n=1}^L N_n \cdot \frac{E^*_{bn}}{E^*_{bi}} \cdot \left(\frac{S}{I}\right)^* \cdot U_n\right) \geq \frac{W}{R}$$

where E^*_{bi} is the received energy per bit for class i traffic, and U_n is the activity ratio for a user with class n traffic (users that belong to the same class of traffic have the same activity ratio). U_n is the activity ratio of the traffic source after transmitter buffer and is related to the original (before buffering) source activity ratio according to the following equation:

Denoted by $\tilde{U}_i$, the activity ratio of class i traffic and assume $\text{prob}(\tilde{U}_i = 1) = \tilde{P}_i$ then

$$\text{Prob}(U_i = 1) = P_i \text{ where } P_i = \tilde{P}_i \cdot \frac{r_i}{R} \quad \text{Eq(4.12)}$$

Π_i can be calculated assuming that the total interference power distribution has a binomial distribution:

$$\Pi_i = P_i \cdot \sum_{k \in S_n=1}^L \prod_{n=1}^L \binom{N_n}{k_n} (P_n)^{k_n} \cdot (1 - P_n)^{N_n - k_n} \quad \text{Eq(4.13)}$$

$$S: \{k\} \text{ where } \sum_{n=1}^L k_n \frac{E^*_{bn}(S)}{E^*_{bi}(\bar{I})_i} \geq \frac{W}{R}$$

where k is a L dimensional user vector, $k = [k_1 \ k_2 \dots k_L]$.

System outage probability in a multimedia CDMA network with fixed processing gain scheme is defined in this thesis as

$$\text{System outage} = \max\{\Pi_i\} \quad \text{for } i = 1, 2, \dots, L \quad \text{Eq(4.14)}$$

The outage probability for a class i user with the variable processing gain transmission scheme, can be calculated similar to the fixed processing gain scheme as

$$\text{Prob}\left(\left(\frac{S}{\bar{I}}\right)_i \leq \left(\frac{S}{\bar{I}}\right)_i^*\right) = \text{Prob}(\tilde{U}_i = 1) \cdot \text{prob}\left(\sum_{n=1}^L N_n \frac{E^*_{bn} \cdot r_n}{E^*_{bi} \cdot r_i} \cdot \left(\frac{S}{\bar{I}}\right)_i^* \cdot \tilde{U}_n \geq \frac{W}{r_i}\right)$$

Denoted by $\tilde{\Pi}_i$ the outage probability for class i user, the system outage probability is defined similarly to the fixed processing gain scheme as

$$\text{System outage} = \max\{\tilde{\Pi}_i\} \quad \text{for } i = 1, 2, \dots, L \quad \text{Eq(4.15)}$$

where $\tilde{\Pi}_i$ is calculated as

$$\tilde{\Pi}_i = P_i \cdot \sum_{k \in S_n} \prod_{n=1}^L \binom{N_n}{k_n} (\tilde{P}_n)^{k_n} \cdot (1 - \tilde{P}_n)^{N_n - k_n}$$

$$S: \{k\} \text{ where } \sum_{n=1}^L k_n \frac{E^*_{bn} \left(\frac{S}{I} \right)_i^*}{E^*_{bi}} \geq \frac{W}{r_i}$$
Eq(4.16)

The system's outage probability for both transmission schemes is calculated and compared numerically. Two classes of traffics are considered, and different combinations of number of users and minimum required signal to interference ratios have been included in the numerical study. Without loss of generality, the energy per bit for a mobile from the i^{th} class of traffic is assumed to be equal to the minimum required signal to interference ratio for the same class of traffic, in other words $E^*_{bi} = \left(\frac{S}{I} \right)_i^*$. The criteria for choosing the value of energy per bit is further explained in the next chapter.

The results presented in Figures 4.4 to 4.7 confirm that the earlier conclusion for the single class of traffic can be extended to the multiple classes of traffic. In other words, as the number of users in a cell increases, the fixed processing gain transmission scheme has smaller system outage probability than the variable processing gain scheme.

A set of simulation experiments was conducted to extend the numerical results for ON-OFF sources to the multimedia traffic considered in this thesis. The results are presented in Figure 4.8. From this figure, one can conclude that for a given set of traffic parameters the fixed processing gain scheme has less outage probability than variable processing gain scheme for large number of mobiles in the cell.

4.7 Conclusion

The main architectural aspects of the system under study were outlined in this chapter.

A novel quality vector is introduced that is suitable for characterizing the quality of a multimedia communication link. A brief theoretical back ground on the calculation methods for S/I in a multimedia CDMA environment is presented. We argued in favor of using white Gaussian approximation in estimating the S/I. A closed form expression for S/I under fixed processing gain transmission regime is derived based on this approximation.

The fixed processing gain and variable processing gain schemes are compared analytically and by using simulations. The main conclusion is that the fixed processing gain scheme has a lower outage probability than the variable processing gain approach for large number of mobiles with real time bursty traffic. Therefore, the fixed processing gain scheme has the potential of supporting more mobiles in a cell than the other alternative if a large outage probability margin is allowed. Because of the simplicity inherent in the fixed processing gain scheme, this scheme is adopted as the underlying transmission scheme in this thesis.

The reader should note that all the algorithms proposed in this thesis are readily extendable to the variable processing gain scheme which is adopted in the third generation CDMA wireless systems as well.

Figure 4.3: Overload probability versus number of users for different minimum required signal to interference ratios

A Single class of Markovian source is considered. Each source has a 40% activity ratio and maximum bit rate of 32 Kbps.

Figure 4.4: Overload probability versus number of users is compared. Two types of Markovian sources are considered.

Equal numbers of users from each class of traffic are present in the cell.

User traffic parameters:

Class 1: Activity ratio: .4
 Minimum require S/I: 5.5 dB
 Bit rate in ON state: 32 Kbps

Class 2: Activity ratio: .2
 Minimum required S/I: 7.5 dB
 Bit rate in ON state: 128 Kbps

Figure 4.5: Overload probability versus number of users is compared. Two types of Markovian sources are considered.

Equal numbers of users from each class of traffic are present in the cell.

User traffic parameters:

Class 1: Activity ratio: .4
 Minimum required S/I: 5.5 dB
 Bit rate in ON state: 32 Kbps

Class 2: Activity ratio: .2
 Minimum required S/I: 9.5 dB
 Bit rate in ON state: 128 Kbps

Figure 4.6: Overload probability versus number of users is compared. Two types of Markovian sources are considered.

The ratio of the number of users from class two traffic to the number of users from class one is 2:1

User traffic parameters:

Class 1: Activity ratio: .4

Minimum required S/I: 5.5 dB

Bit rate in ON state: 32 Kbps

Class 2: Activity ratio: .2

Minimum required S/I: 9.5 dB

Bit rate in ON state: 128 Kbps

Figure 4.7: Overload probability versus number of users is compared. Two types of Markovian sources are considered.

The ratio of number of users from class two traffic to the number of users from class one is 1:2

User traffic parameters:

Class 1: Activity ratio: .4
 Minimum required S/I: 5.5 dB
 Bit rate in ON state: 32 Kbps

Class 2: Activity ratio: .2
 Minimum required S/I: 9.5 dB
 Bit rate in ON state: 128 Kbps

Figure 4.8: Overload probability versus number of users is compared.

Three types of traffic are considered. Equal numbers of users from each class of traffic are present.

User traffic parameters:

- class 1: Continuous variable rate traffic generated from an auto-regressive model with minimum required $(S/I)=7.5$ dB and maximum bit rate of 128 Kbps
- class2: Fixed rate traffic with 32 Kbps bit rate and minimum required $(S/I)=5.5$ dB
- class 3: Voice traffic with an activity ratio of .4 and a maximum bit rate of 32 Kbps minimum required $(S/I)=4$ dB

Chapter 5

Non-linear power assignment and access control for multimedia CDMA wireless networks

5.1 Introduction

In this chapter, we study the power management and admission control in an outdoor cellular CDMA network, supporting bursty real-time multimedia traffic.

A power control framework is developed that takes into consideration both average and outage requirements of bursty traffic. The power control problem is formulated as a non-linear optimization problem where the total average power transmitted by the users is the objective function that should be minimized. Certain constraints are defined for this optimization according to the average S/I and outage requirements of the users.

A distributed admission control algorithm is also proposed where only a minimum amount of control information is needed to be exchanged among the base stations. A tight analytical upper-bound for the solution of the power assignment problem is found. Admission control is carried out at the base stations using the calculated upper-bounds for the power levels. It is shown that the proposed admission control when coupled with the power assignment algorithm can provide the guaranteed QOS required by the users.

In section 2, the main advantages of using power assignment as a method for providing diverse quality of service for multimedia traffic in CDMA networks is discussed briefly. In section 3, we present the power assignment problem formulation. In section 4, the proposed power control strategy is outlined. The admission control algorithm is presented in section 5. Conclusions follow in section 6.

5.2 Variable quality of service (by power assignment)

In a multimedia communication, different types of media require a different level of error protection; for example, at the application layer, video traffic usually requires more reliability than an audio stream.

Several coding schemes have been proposed for providing Unequal Error Protection(UEP)

[63]. However, in most of the proposed schemes such as Algebraic Unequal Error Protection codes, the complexity grows exponentially with the number of protection levels. Punctured convolutional codes [39] can provide unequal error protection by changing the coding rate, i.e., in order to provide enhanced reliability, the coding rate is reduced. However, for a given information rate, this scheme requires bandwidth expansion; considering the bandwidth limit in a wireless environment, this approach may become inefficient. In addition to bandwidth efficiency, a UEP variable rate channel coder has suboptimal coding gain in comparison with a fixed rate coder [109].

Power assignment and power control in a CDMA environment have been proposed as an efficient technique for providing variable quality of services for the users [18][51][95][106][109].

It was mentioned in the previous chapters that CDMA capacity is limited by interference. This observation suggests that raising the received power from a user at the cell site will reduce the bit error rate. The purpose for power assignment algorithms in multimedia communications is to provide variable QOS by modulating the user's power level. In other words, a user requiring a high quality communication link is assigned more power than a user requiring a low quality link [109].

There are many advantages in using power assignment to provide UEP. The main advantage is its simplicity. The decoder at the cell site can perform detection without the knowledge of the code rate; furthermore, there is no need for a special packet framing structure for hierarchical UEP coding. In addition, the advantage of fine granularity and wide range of bit error rates is achievable in this scheme [109].

5.3 Power assignment problem formulation

Power assignment for multimedia CDMA was proposed originally in [51][106][109]. In the proposed schemes, different average signal to interference ratios are provided for the users through power assignment, while the total transmitted power by the users is minimized. In these papers, it has been assumed that perfect power control is in place and only fixed rate traffic is considered. In this section, the formulation presented in [51][109] is extended to accommodate both the statistical variation in the user bit rate and variation in the user's power due to the imperfect power control in the cell.

Consider a CDMA cellular network with M cells and N_j ; $j = 1, 2, \dots, M$ users in each cell. The power assignment problem can be formulated as an optimization problem where

the objective is to minimize the total average power transmitted by all users. The problem can be stated as follows.

Find a set of energy per bit values $\{E_{bij}\}$ $i = 1, 2, \dots, N_j$ and $j = 1, 2, \dots, M$ that minimizes the total average transmit power from all the users, subject to constraints (1) and (2) below. The average power is given as

$$P_{ave} = \sum_{j=1}^M \sum_{i=1}^{N_j} E_{bij} \cdot h_{ij} \cdot \bar{r}_{ij} \quad \text{Eq(5.1)}$$

where h_{ij} is the path loss encountered by user i in the j^{th} cell and $\bar{r}_{ij}$ is the average bit rate of the same user.

The two constraints are

$$(1) \quad \overline{(S/I)}_{ij} \geq (S/I)_{ij}^+ \quad (i = 1, 2, \dots, N_j) \quad (j = 1, 2, \dots, M)$$

$$(2) \quad \text{Prob}[(S/I)_{ij} \leq (S/I)_{ij}^*] \leq L_{ij} \quad (i = 1, 2, \dots, N_j) \quad (j = 1, 2, \dots, M) \quad \text{Eq(5.2)}$$

where $(S/I)_{ij}$ is the instantaneous signal to interference ratio encountered by user i in cell j . $\overline{(S/I)}_{ij}$ is the average value of $(S/I)_{ij}$, and $(S/I)_{ij}^*$ is the minimum acceptable signal to interference ratio for user i for an outage probability threshold equal to L_{ij} . $(S/I)_{ij}^+$ is the acceptable average signal to interference ratio for the same user.

It is assumed that each user is actively communicating with one base station only. We further assume that the base stations are selected in an optimum way.

In order to solve the optimization problem, the two constraints should be expressed in terms of optimization variables $\{E_{bij}\}$. In the rest of this section, expressions for average signal to interference ratio and outage probability are derived in terms of $\{E_{bij}\}$ and underlying assumptions are stated.

The average signal to interference ratio can be calculated using the assumption that it is equal to the ratio of average desired user power to the average interference power.

$$\overline{(S/I)}_{ij} = \frac{E_{bij} \cdot h_{ij} \cdot \overline{r_{ij}}}{\frac{\overline{r_{ij}}}{W} \left[\overline{\sigma_j^2} + \sigma_T^2 + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot h_{mj} \cdot \overline{r_{mj}} \right]} \quad \text{Eq(5.3)}$$

where W is the total available transmission bandwidth and $\overline{\sigma_j^2}$ is the average inter-cell interference received at the j^{th} cell, σ_T^2 is the background noise which is assumed to be constant across all cells. Therefore, the first constraint can be expressed in terms of $\{E_{bij}\}$ as:

$$\frac{(S/I)_{ij}}{W} + \left[\frac{\overline{\sigma_j^2} + \sigma_T^2}{h_{ij}} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot \frac{h_{mj}}{h_{ij}} \cdot \overline{r_{mj}} \right] \leq E_{bij} \quad \text{Eq(5.4)}$$

We can also write $\overline{\sigma_j^2}$ in terms of $\{E_{bij}\}$ as follows:

$$\overline{\sigma_j^2} = \sum_{\substack{k=1 \\ k \neq j}}^M \sum_{i=1}^{N_k} E_{bik} \cdot \overline{r_{ik}} \cdot h_{ik}^{(j)} \quad \text{Eq(5.5)}$$

$h_{ik}^{(j)}$ is the path gain/loss for user i in cell k with respect to the base station in cell j .

Due to the fact that the fixed processing gain scheme is adopted in the cell, instantaneous power level of a user can be expressed as $P_{ij} = E_{bij} \cdot R \cdot U_{ij}$ where R is the fixed channel transmission rate and U_{ij} is a binary random variable whose probability density function (PDF) can be approximated as

$$\begin{aligned} \text{prob}[U_{ij} = 1] &= \frac{\overline{r_{ij}}}{R} = \pi_{ij} \\ \text{prob}[U_{ij} = 0] &= 1 - \frac{\overline{r_{ij}}}{R} = 1 - \pi_{ij} \end{aligned} \quad \text{Eq(5.6)}$$

Using the total probability law, the outage constraint (constraint 2) in a cell can be rewritten as

$$\pi_{ij} \cdot \text{prob}\left(\left[\frac{I_{ij}}{W}\right]^{-1} \leq \frac{(S/I)_{ij}^*}{E_{bij}}\right) \leq L_{ij} \quad \text{Eq(5.7)}$$

where

$$I_{ij} = \left[\frac{\sigma_j^2 + \sigma_T^2}{h_{ij}} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot \frac{h_{mj}}{h_{ij}} \cdot R \cdot U_{mj} \right]$$

σ_j^2 is the instantaneous interference random variable (inter-cell interference) in the j^{th} cell.

Assuming that the total interference power $\{I_{ij}\}$ has a Gaussian distribution [17], Eq(5.7) (after some mathematical manipulation) can be written in the following form:

$$\frac{(S/I)_{ij}^*}{W} \left[\text{Sqrt}(\text{Var}(I_{ij})) \cdot Q^{-1}\left(\frac{L_{ij}}{\pi_{ij}}\right) + \bar{I}_{ij} \right] \leq E_{bij} \quad \text{Eq(5.8)}$$

where $Q^{-1}(\cdot)$ is the inverse Q function

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-x^2/2} \cdot dx \quad \text{Eq(5.9)}$$

$\text{Var}(I_{ij})$ and $\bar{I}_{ij}$ are the variance and mean value of the random variable I_{ij} .

The inequalities expressed in Eq(5.4) and Eq(5.8) are the final forms of the constraints that will be used in the optimization problem.

5.4 Non-linear power control technique

Because the outage constraint is a non-linear function of energy per bits, the power assignment problem as a whole is a non-linear optimization problem. In this section, we present an iterative algorithm to solve the power assignment problem which can be implemented in a distributed manner [60]. A closely related work is reported in [68].

5.4.1 Iterative algorithm

Eq(5.4) and Eq(5.8) indicate that a necessary and sufficient condition for $\{E_{bij}\}$ to be a solution for the non-linear optimization problem presented in Eq(5.1) and Eq(5.2) can be

expressed as

$$E_{bij} \geq I_{ij}^e \quad i = 1, 2, \dots, N_j \quad j = 1, 2, \dots, M \quad \text{Eq(5.10)}$$

I_{ij}^e is called the effective interference function. It will be shown later that the introduction of this function allows us to extend the power control framework developed by Yates [107] to the non-linear case. I_{ij}^e is defined as

$$I_{ij}^e = \max(I_{ij}^{ave}, I_{ij}^{out})$$

where

$$I_{ij}^{ave} = \frac{(S/I)_{ij}}{W} \left[\frac{\sigma_j^2 + \sigma_T^2}{h_{ij}} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot \frac{h_{mj}}{h_{ij}} \cdot \overline{r_{mj}} \right] \quad \text{Eq(5.11)}$$

$$I_{ij}^{out} = \frac{(S/I)_{ij}^*}{W} \left(\left[\text{Sqrt}(\text{Var}(I_{ij})) \cdot Q^{-1}\left(\frac{L_{ij}}{\pi_{ij}}\right) + \overline{I_{ij}} \right] \right)$$

Let $\mathbf{I}^e$ denote an effective interference vector defined as

$$\mathbf{I}^e = [I_{11}^e, I_{21}^e, \dots, I_{ij}^e, \dots, I_{N_M M}^e] \quad \text{Eq(5.12)}$$

and let $\mathbf{E}_b$ be the vector of energy per bit for the users in the network:

$$\mathbf{E}_b = [E_{b11}, E_{b21}, \dots, E_{bij}, \dots, E_{bN_M M}] \quad \text{Eq(5.13)}$$

It can easily be verified that the following properties are satisfied by $\mathbf{I}^e$:

- 1) positivity: $\mathbf{I}^e > 0$
- 2) Monotonicity: if $\mathbf{E}_b \geq \mathbf{E}_b'$ then $\mathbf{I}^e(\mathbf{E}_b) \geq \mathbf{I}^e(\mathbf{E}_b')$
- 3) Scalability: for all $\Upsilon \geq 1$ $\Upsilon \cdot \mathbf{I}^e(\mathbf{E}_b) > \mathbf{I}^e(\Upsilon \mathbf{E}_b)$

where $>$ is applied on a component by component basis.

Using the theorems given in reference [107], it can be shown that when the three conditions stated above are satisfied, the following iterative algorithm converges to the minimum power solution:

$$E_b(n+1) = I^e(E_b(n)) \quad \text{Eq(5.14)}$$

where $E_b(n)$ is the value of E_b at the n^{th} iteration. The proposed iterative algorithm requires the value of effective interference experienced by each mobile at the base station to be measured. This requirement necessitates the mean estimation of mean and variance of interference power for each mobile at each iteration. The third parameter that is needed to be known at the base station is the value of each mobile's link gain/loss.

5.4.2 Imperfect power control

In the proposed non-linear power assignment algorithm, it was assumed that the underlying power control implementation was perfect. In other words, at each iteration the received energy per bits from the mobiles conforms exactly with the target values derived from Eq(5.14).

In a practical system, there are always errors in closed loop power control. Imperfect power control will result in random fluctuations in the received power at the base station around its target value. It has been shown that the power fluctuation can be modeled satisfactorily by a lognormal distribution [101].

In this subsection, the analytical framework for non-linear power assignment is extended to include the effect of imperfect power control. The power assignment problem can be re-formulated as follows.

Find a set of energy per bit $\{E_{bij}\}$ for the users such that

$$\overline{(S/I)}_{ij} = \frac{E_{bij} \cdot 10^{\overline{\zeta_{ij}/10}} \cdot \overline{h_{ij}} \cdot \overline{r_{ij}}}{\overline{\frac{r_{ij}}{W}} \left[\overline{\sigma_j^2} + \sigma_T^2 + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot 10^{\overline{\zeta_{mj}/10}} \cdot \overline{h_{mj}} \cdot \overline{r_{mj}} \right]} \geq \left(\frac{S}{I} \right)_{ij}^+ \quad \text{Eq(5.15)}$$

$i = 1, \dots, N_j \quad j = 1, \dots, M$

and

$$\begin{aligned}
 & \text{Prob}[(S/I)_{ij} \leq (S/I)_{ij}^*] \leq L_{ij} \quad \text{where} \\
 & (S/I)_{ij} = \frac{E_{bij} \cdot 10^{\zeta_{ij}/10} \cdot h_{ij} \cdot U_{ij}}{\frac{1}{W} \left[\sigma_j^2 + \sigma_T^2 + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot 10^{\zeta_{mj}/10} \cdot h_{mj} \cdot R \cdot U_{mj} \right]} \quad \text{Eq(5.16)}
 \end{aligned}$$

It is assumed that under the imperfect power control scenario, the received power is related to the target power level as

$P_{received} = P_{target} \cdot 10^{\zeta/10}$ where ζ is a zero mean Gaussian random variable with standard deviation in the range of 0~2 dB.

$\overline{\sigma_j^2}$ is the total average inter-cell interference received at the j^{th} cell. Following the same methodology as the perfect power control scenario, the average constraints expressed in Eq(5.15) can be simplified as

$$\frac{(S/I)_{ij}^+}{W} \left[\frac{\overline{\sigma_j^2} + \sigma_T^2}{h_{ij}} \cdot 10^{\zeta_{ij}/10} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} E_{bmj} \cdot \frac{h_{mj}}{h_{ij}} \cdot (10^{2\zeta_{mj}/10}) \cdot \overline{r_{mj}} \right] \leq E_{bij} \quad \text{Eq(5.17)}$$

$\overline{\sigma_j^2}$ in the j^{th} cell can be written in terms of $\{E_{bij}\}$ in the other cells as:

$$\overline{\sigma_j^2} = \sum_{\substack{k=1 \\ k \neq j}}^M \sum_{i=1}^{N_k} E_{bik} \cdot 10^{\zeta_{ik}/10} \cdot \overline{r_{ik}} \cdot h_{ik}^{(j)} \quad \text{Eq(5.18)}$$

$h_{ik}^{(j)}$ is the path loss for the user i in cell k with respect to the cell site in cell j .

To derive the above inequality, it is assumed that the lognormal element of the received energy per bit in the numerator of equation (5.15) can be factored out; in practice, factoring out the numerator may not always be possible. Without this assumption, the derivation of average and outage constraints becomes excessively complex.

The outage constraint expression for the mobile i in the j^{th} cell can be modified, as follows, to take into consideration the effect of imperfect power control:

$$\frac{(S/I)_{ij}^*}{W} \left[\text{Sqrt}(\text{Var}(I_{ij})) \cdot Q^{-1}\left(\frac{L_{ij}}{\pi_{ij}}\right) + \bar{I}_{ij} \right] \leq E_{bij} \quad \text{Eq(5.19)}$$

with the following new definition for the I_{ij}

$$I_{ij} = \left[\frac{\sigma_j^2 + \sigma_T^2}{h_{ij}} \cdot 10^{\zeta_{ij}/10} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} \frac{E_{bmj}}{h_{ij}} \cdot (10^{2\zeta_{ij}/10}) \cdot h_{mj} \cdot R \cdot U_{mj} \right] \quad \text{Eq(5.20)}$$

σ_j^2 is the instantaneous inter-cell interference random variable in the j^{th} cell. Gaussian distribution for the total power of interference $\{I_{ij}\}$ is assumed to remain valid in this derivation.

The effective interference function is defined similarly to the perfect power control scenario as

$$I_{ij}^e = \max(I_{ij}^{\text{ave}}, I_{ij}^{\text{out}}) \quad \text{Eq(5.21)}$$

where

$$I_{ij}^{\text{ave}} = \frac{(S/I)_{ij}^+}{W} \left[\frac{\overline{\sigma_j^2 + \sigma_T^2}}{h_{ij}} \cdot \overline{10^{\zeta_{ij}/10}} + \sum_{\substack{m=1 \\ m \neq j}}^{N_j} E_{bmj} \cdot \frac{h_{mj}}{h_{ij}} \cdot \overline{(10^{2\zeta_{ij}/10})} \cdot \overline{r_{mj}} \right] \quad \text{Eq(5.22)}$$

$$I_{ij}^{\text{out}} = \frac{(S/I)_{ij}^*}{W} \left(\frac{\sigma_j^2 + \sigma_T^2}{h_{ij}} \cdot 10^{\zeta_{ij}/10} + \sum_{\substack{m=1 \\ m \neq i}}^{N_j} \frac{E_{bmj}}{h_{ij}} \cdot (10^{2\zeta_{ij}/10}) \cdot h_{mj} \cdot R \cdot U_{mj} \right)$$

Following the same rationale as in the previous section, it can be shown that the following iterative algorithm will converge to the minimum power solution:

$$E_b(n+1) = I^e(E_b(n)) \quad \text{Eq(5.23)}$$

where $E_b(n)$ is the value of E_b at the n^{th} iteration, and $I^e = [I_{11}^e, I_{21}^e, \dots, I_{ij}^e, \dots, I_{N_M M}^e]$ is the effective interference vector in a network of M cells.

5.5 Admission control

In CDMA networks, the power assigned to each mobile affects the signal to interference ratios of all the other mobiles in the network. Therefore, the power control process should ideally be applied at a center point that oversees the entire system. Because this approach is not practical in many cases, we seek a suboptimal distributed approach.

The power control is essentially an interference management process. Because adding new terminals contributes to the interference environment, admitting new users and controlling the power of existing users are inter-related processes. Moreover, on optimum admission control algorithm should be central to the whole system. The rationale for having a central admission control is the same rationale that favors central power control. Again, for practical reasons, we seek a distributed admission policy.

The main focus of a distributed admission control scheme is the development of an algorithm that can predict the power vector (resulting from non-linear power assignment scheme) after the arrival of a new mobile without actually allowing the new mobile to enter the cell.

Definitions and assumptions:

The traffic state of the j^{th} cell in a network of M cells with NC classes of traffic is characterized by an active user vector $N_j = [n_1 \ n_2 \dots n_{NC}]$ where n_k is the number of mobiles that belong to the k^{th} class of traffic in the j^{th} cell. Furthermore, the power state of the j^{th} cell is characterized by a $(1, NC+1)$ vector which is composed of the current received energy per bit vector $(E_b^*)_j = [E_{b_{1,j}}^* \ E_{b_{2,j}}^* \dots E_{b_{NC,j}}^*]$ and a maximum power coefficient $(\alpha_{max})_j \ j = 1, 2, \dots, M$ which determines the power ceiling in a cell.

The received energy per bit is calculated based on the transmitter's energy per bit for the i^{th} mobile in the j^{th} cell as

$$E^*_{bij} = E_{bij} \cdot h_{ij} \quad \begin{array}{l} i = 1, 2, \dots, N_j \\ j = 1, 2, \dots, M \end{array} \quad \text{Eq(5.24)}$$

By grouping the $\{E_{bij}\}$ and h_{ij} based on the corresponding class of traffic Eq(5.24) can be written as

$$E^*_{bk,j} = E_{bmk,j} \cdot h_{mk,j} \quad \begin{array}{l} m = 1, 2, \dots, n_k \\ j = 1, 2, \dots, M \\ k = 1, 2, \dots, NC \end{array} \quad \text{Eq(5.25)}$$

where $E^*_{bk,j}$ is the received energy per bit for the k^{th} class of traffic in the j^{th} cell.

The rationale behind choosing the received energy per bit as part of the power state vector is that each class of traffic has the same received energy per bit at the base station, which results in a smaller size state space than if using the transmitter energy per bit.

The maximum power coefficient in the j^{th} cell is calculated as the maximum ratio that the received power vector can be scaled to without violating the maximum transmitter power limit in the cell.

$$\alpha_{\max,j} = \min\{\Upsilon_{mk,j}\} \quad \text{where} \quad \left[\Upsilon_{mk,j} = \frac{\text{power limit}}{\frac{E^*_{bk,j} R}{h_{mk,j}}} \right] \quad \begin{array}{l} m = 1, 2, \dots, n_k \\ k = 1, 2, \dots, NC \end{array}$$

A power vector in a cell (j^{th} cell) is called admissible if

$$E^*_{bk,j} \leq \frac{\text{Power limit} \cdot h_{mk,j}}{R} \quad \begin{array}{l} m = 1, 2, \dots, n_k \\ k = 1, 2, \dots, NC \end{array}$$

5.5.1 Linear approximation for power increase

Upon the arrival of a new user, the power vector in the network will change. The components of the received power vector will increase and the maximum power coefficient will decrease.

The objective of admission control is to ensure that the power vectors in the cell of arrival and all the neighboring cells are admissible. A user should be rejected if it forces some of the already admitted mobiles to exceed their power limit.

Mathematically, the increase in the power vector of the j^{th} cell due to the admittance of a new mobile can be represented as a difference vector and is denoted by $\Delta E^*_{bk,j}(N + \vec{1}_i)$, where $\vec{1}_i$ is an all zero row vector with a “one” in the i^{th} element.

$$E^*_{bk,j}(N + \vec{1}_i) = (E^*_{bk,j}(N) + \Delta E^*_{bk,j}(N + \vec{1}_i))$$

Due to the non-linearity inherent in the power assignment algorithm, a closed form expression for the $E^*_{bk,j}(N + \vec{1}_i)$ could not be derived. We propose to replace the differential vector by an upper bound expression that is easy to calculate in real-time. Our simulation study indicates that a linear expression is an effective and simple upper bound for the differential vector:

$$\Delta E^*_{bk,j}(N + \vec{1}_i) \leq \xi_j \cdot E^*_{bk,j}(N)$$

or

Eq(5.26)

$$E^*_{bk,j}(N + \vec{1}_i) \leq \alpha_j \cdot E^*_{bk,j}(N) \quad \text{where } \alpha_j = 1 + \xi_j$$

The derivation method of an appropriate α_j that provides a tight upper bound for the differential vector is explained in the next section. Furthermore, we show that by using α_j and periodic exchange of $\alpha_{max,j}$ $j = 1, 2, \dots, M$ among the base stations, an effective distributed admission control that can provide guaranteed QOS for the mobiles is achieved.

5.5.2 Distributed admission control with exchange of maximum power coefficients among the base stations

This section outlines a novel distributed admission control scheme and provides its theoretical foundations.

Lemma1: If the received power level in a cell (from the mobiles in the cell only) is increased by a factor Γ , then the inter-cell interference power increases by a ratio (resulting from non-linear power assignment) that is less than or equal to Γ .

Lemma2: If there exist $\alpha_j \geq 1$ and $\alpha_j \leq \alpha_{max,j}$; $j = 1, 2, \dots, M$ where α_j satisfies the following 2NC inequalities, then there exists a minimum power solution for the global non-linear power assignment (after arrival of a new mobile in the j^{th} cell) that satisfies both average and outage constraints as well as the power limits.

$$\alpha_j \geq \frac{\frac{(S/I)_{ij}^+}{E_{b,i,j}^* W} \sigma_T^2}{\left[1 - \frac{(S/I)_{ij}^+}{E_{b,i,j}^* W} [Y_{ij}] - \frac{(S/I)_{ij}^+}{E_{b,i,j}^* W} \sigma_j^2 \right]} \quad i = 1, 2, \dots, NC \quad \text{Eq(5.27)}$$

where

$$Y_{ij} = \sum_{\substack{k=1 \\ k \neq i}}^{NC} n_k E_{b,k,j}^* \cdot \bar{r}_{kj} + (n_i - 1) \cdot E_{b,i,j}^* \cdot \bar{r}_{ij}$$

and

$$\alpha_j \geq \frac{\frac{(S/I)_{ij}^*}{E_{b,i,j}^* W} \sigma_T^2}{\left[1 - \frac{(S/I)_{ij}^*}{E_{b,i,j}^* W} [Q^{-1}(Z_{ij}) \cdot STD(X_{ij}) + \bar{X}_{ij}] \right]} \quad i = 1, 2, \dots, NC$$

where

$$X_{ij} = \frac{1}{W} \left[\sum_{\substack{k=1 \\ k \neq i}}^{NC} n_k E_{b,k,j}^* \cdot R \cdot U_k + (n_i - 1) E_{b,i,j}^* \cdot R \cdot U_i + \sigma_j^2 \right]$$

$\bar{X}_{ij}$ and $STD(X_{ij})$ are the mean and standard deviation of the random variable X_{ij} , U_j is the activity ratio random variable corresponding to the j^{th} source traffic.

The parameter Z_{ij} is defined as $Z_{ij} = L_{ij}/\pi_{ij}$. $(S/I)_{ij}^*$ and $(S/I)_{ij}^+$ are the minimum and average required signal to interference ratio by the i^{th} class of traffic. n_k and $E_{b,k,j}^*$ are the total number of users from class k and received energy per bit from the same class of traffic. σ_j^2 and $\bar{\sigma}_j^2$ are the instantaneous and average inter-cell interference in the j^{th} cell.

Proof for these lemmas can be found in appendix (A).

Based on these lemmas, the following call admission control strategy is proposed in this chapter.

Maximum power coefficients $\alpha_{max,j}$ ($j = 1, 2, \dots, M$) should be exchanged among the base stations periodically. This will provide an up-to-date table of the power ceiling available at each base station.

Upon the arrival of a new mobile in a cell, the average S/I and outage performance requirement of the new mobile should be determined and consequently its class of traffic will be identified.

The minimum value of α_j that satisfies all the 2NC requirements should be found. If α_j is larger than one and smaller than all the elements of the maximum power coefficient table available at the base station, then the user is admitted and is guaranteed its average and outage performance requirements during its call duration.

It should be noted that the calculation of 2NC inequalities may not be necessary at every call request event. Because only one of the inequalities represents the bottleneck class of traffic, then if the bottleneck constraint is identifiable, it is necessary to calculate only one inequality.

Initial value problem:

So far, it has been assumed that the new mobile belongs to one of the already active traffic classes in the cell, and an $E^*_{bk,j}$ derived from the non-linear power assignment exists for that class of traffic. In this sub-section, the problem of admission control when a new class of traffic enters the cell (an event with low probability) is analyzed, and a solution is proposed.

Because there is no E^*_b corresponding to the class of the new mobile's traffic, therefore the previous model of a linear upper bound for the power increase is not directly applicable.

To circumvent this problem, an initial value for the received energy per bit for the new class of traffic is used. There are certain conditions that the initial value should satisfy. A very small initial value will result in a very large power increase coefficient α_j and a very large value will result in a negative α_j . In both cases the new call will be blocked.

We propose to set the initial value of the energy per bit for the new class of traffic equal to $E^*_{bk} = \Upsilon^* \cdot \left(\frac{S}{I}\right)_k^+$ where $\left(\frac{S}{I}\right)_k^+$ is the required average S/I for the new class of traffic. Υ^* is calculated as

$$\gamma^* = \max \left\{ \frac{E^* b_k}{\left(\frac{S}{I} \right)_k^+} \right\} \quad k = 1, 2, \dots, NC$$

This formula is based on the observation that the received energy per bit vector without outage constraints (only average required S/I) is approximately a linear function of the target average S/I or $\left(\frac{S}{I} \right)_k^+$ [109]. We found this approximation to be a reasonably effective method for setting the initial values.

5.6 Numerical Results

Two sets of numerical experiments are conducted to investigate the effectiveness of the proposed power and admission control framework. The first set of numerical results highlights different aspects of the proposed power control algorithm. The main emphasis is to show the impact of including traffic statistics in the power assignment process.

The second set of numerical results demonstrates the effectiveness of the proposed distributed admission control combined with power assignment in providing the required QOS for the mobiles. The efficient utilization of the cell capacity is demonstrated as well.

Three classes of traffic are assumed to be present in the network. Type (1) traffic (variable rate video), is assumed to have an average S/I requirement of 8.5 dB ($(S/I)^+ = 8.5$ dB) and minimum acceptable threshold of 7 dB ($(S/I)^* = 7$ dB). For the second type of traffic (fixed rate video) the average and minimum required signal to interference ratios are set equal to 7 dB and 5.5 dB. The corresponding values for the third class of traffic (voice) are set as $(S/I)^+ = 5$ dB and $(S/I)^* = 3.5$ dB.

The first group of numerical experiments is aimed at demonstrating the effect of including the outage probability constraints in the power control mechanism in addition to the average S/I requirements.

The total received power at a cell site, with or without outage constraints, is derived at the base stations in the four inner base stations and is averaged over one thousand realizations of user locations in the network. The user locations at each trial are assumed to be uniformly distributed over the network area. Furthermore, each user is assumed to belong to each class of traffic with equal probability. The ratio of received power with outage constraint to the received power when only average S/I constraints are considered is presented in Figure 5.1. These experiments were carried out for three different outage

probability thresholds. The outage probability thresholds were assumed to be the same for all the traffic classes at each trial.

As one could expect, the smaller the outage threshold the more significant the effect of the outage requirement on the users' power level will be. In other words, users should transmit at a higher power level to satisfy their outage requirements; the non-linear constraints become the dominant restriction compared to the average requirements.

The convergence speed of the proposed algorithm is presented in Fig(5.2). Similarly to the previous experiments, the results are averaged over one thousand realizations of the user locations. Infeasible cases are excluded from the averaging. The initial value of E_b^* is set equal to zero at the beginning of each trial.

The infeasibility probability for the iterative technique is presented in Fig(5.3). Infeasibility probability is defined as the probability that the power assignment problem does not have a bounded solution. Results are based on one thousand trials for each outage threshold.

The actual outage probability and average signal to interference ratios achieved when the non-linear power assignment algorithm is used as underlying power assignment method are shown in Fig(5.4). The results are based on three different outage probability thresholds.

The impact of imperfect power control on non-linear power assignment is studied, and results are reported in Figures 5.5 to 5.7. Lognormal shadowing with 4 dB standard deviation is considered in these set of experiments. From these figures one can draw two conclusions. First, imperfect power control causes significant degradation in the performance of the power assignment algorithm. Slower convergence speed and higher required transmit power and infeasibility probability are experienced when power control is not perfect. The second observation is that the adverse effect of imperfect power control is proportional to the standard deviation value of the lognormal random variable that models the imperfect power control effect.

The second set of numerical experiments is aimed at evaluating the effectiveness of the proposed combined admission/power control framework. Blocking probability is used as the performance metric to evaluate the admission control effectiveness. Blocking probability versus traffic intensity for different parameters like the transmitters power limit as well as the outage probability thresholds are estimated.

The blocking probability achieved under the distributed admission control algorithm is compared with an ideal centralized scheme.

All the new mobiles requesting a connection are allowed to enter the cell tentatively under the centralized admission control regime. If any mobile's performance degrades below the acceptable limit (anywhere in the network) after the power assignment algorithm executes, the new arrival will be rejected; otherwise, it will be admitted. Full knowledge of link gains and source traffic statistics is assumed in a central node. This scheme, although impractical, will provide the minimum possible blocking probability for a given traffic arrival intensity.

The average blocking probability under distributed and centralized admission control is found for different power limits for the transmitters. Results are shown in Fig(5.8). The blocking probability is averaged over the blocking experienced by three classes of traffic sources. It is assumed that the outage probability threshold is the same for all three classes of traffic. Background noise power was set equal to -128 dBm and total antenna gain (receiver + transmitter) was assumed to be 8dB. Shadowing is not considered in this experiment and perfect power control is assumed. From this figure one can conclude that the blocking probability achieved under the distributed admission control algorithm is fairly close to that of the centralized scheme outcome.

Under similar conditions as the previous experiment, the average blocking probability when each class of traffic has a different outage threshold requirement is derived and shown in Figure 5.9. The transmitter power limit is set at one watt. The results of this experiment confirm that even facing diverse outage requirements by the mobiles, the distributed admission control algorithm can achieve good results close to the centralized scheme. This result is significant, because using an admission control based on the upper bounds could lead to a highly conservative scheme when there is wide variation of outage requirements.

The value of outage and average S/I achieved in this experiment is shown in Fig (5.10), which demonstrates that all the classes of traffic source attained their required outage probability and average S/I requirements.

5.7 Conclusion

In this chapter power assignment and admission control in a CDMA environment when bursty multimedia traffic is supported are addressed. A novel power assignment

framework is developed that directly takes into consideration the statistics of the source traffic in order to provide the outage probability as well as the average S/I requirements of bursty traffic.

A distributed call admission control that regulates the admission of the new mobiles in the network is proposed. It is shown that the access control algorithm can provide guaranteed quality of service for different classes of traffic. The efficiency of the proposed algorithm is demonstrated by comparing the blocking probability resulting from the distributed admission control to that of a centralized scheme.

Figure 5.1: Ratio of received power with outage constraints to the received power with average constraints only

Figure 5.2: Convergence speed of power assignment algorithm

Figure 5.3: Probability of infeasibility for power assignment algorithm

Outage and average S/I for variable rate video traffic source

Outage and average S/I for fixed rate video traffic source

Outage and average S/I for voice traffic source

Figure 5.4: Outage probability and S/I achieved under non-linear power assignment algorithm

Figure 5.5: Probability of infeasibility for power assignment algorithm (imperfect power control) with different standard deviation parameter for lognormal variation

Figure 5.6: The ratio of received power with outage constraints to the received power with average constraints only (Imperfect power control)

Figure 5.7: Convergence speed of power assignment algorithm (Imperfect power control)

Centralized scheme

Distributed scheme

Figure 5.8: Blocking probability for distributed and centralized access scheme

(Outage probability threshold is the same for all three classes of traffic)

Figure 5.9: Blocking probability for different classes of traffic with different outage thresholds

Outage thresholds in
Figures (5.9) & (5.10)

Outage threshold for variable rate video traffic: .0005

Outage threshold for fixed rate video traffic: .001

Outage threshold for voice traffic: .005

Figure 5.10: Outage and average S/I for different classes of traffic with different outage thresholds

Three classes of traffic in the network:

variable rate video (v-video) fixed rate video (f-video) voice

Chapter 6

Linear power assignment and mobile admission criteria

6.1 Introduction

The proposed non-linear power assignment in the last chapter is an optimum scheme in utilizing the cell capacity. However, the applicability of the non-linear power assignment algorithm could be limited due to the following reasons:

- (a) The non-linear power assignment algorithm relies on a statistical model for the interference power, namely the Gaussian model, which may not be accurate in some cases.
- (b) Because the statistical estimation of the source traffic is incorporated into the power control algorithm, the second order statistics (variance) of the interference power should be estimated in a very short period of time (power control iteration interval).
- (c) The power assignment algorithm should be executed every time that there is a change in the interference level at the base station due to the user movement or to a change in the number of mobiles in the network. Computational complexity due to the frequent calculation of second order statistics can become a detrimental factor in employing the non-linear power assignment algorithm.

In this chapter and the next, an alternative algorithm is developed. The main concept in this proposal, which is called linear power assignment and adaptive access control in this thesis, is based on de-coupling the tasks of providing the required average S/I and outage requirements by the mobiles as much as possible.

The required average S/I is satisfied with the help of a robust and simple power assignment scheme. A two layer call admission control framework is developed to regulate the access of the mobiles in the network. A deterministic admission control guarantees the feasibility of the power assignment algorithm. The second layer of admission control, which is probabilistic in nature, regulates the admission of the mobiles in the cell so that the outage requirements are satisfied as well.

Because the power assignment is based on the average S/I requirements only, the second and third problem inherent in the non-linear power assignment will be avoided. Furthermore, because outage performance is provided through a call admission process, it is possible to employ some of the existing probability density estimation algorithms to estimate the outage probability experienced by the mobiles. This approach is made

possible by fact that the admission control algorithm is executed every time a mobile requests a connection and to the fact that the time scale of call inter-arrival is much longer than the power control iteration time. Using a probability density estimator will eliminate the need for a statistical model in the power assignment algorithm.

In this chapter, a linear power assignment algorithm where mobiles' power levels are set according to their average required S/I is introduced, and different aspects of this method of power assignment are discussed.

A set of equations that define the cell capacity limit are found. Cell capacity is defined in terms of the maximum number of admissible mobiles in the cell from each class of traffic.

Another contribution in this chapter is the development of a tele-traffic model for a CDMA cell supporting multimedia traffic. The traffic model is constructed using the cell capacity equations.

The second part of the linear power assignment and adaptive access control algorithm, namely the access control, is addressed in the next chapter.

6.2 Optimum linear power assignment problem

The proposed linear power assignment algorithm solves the power assignment problem with the assumption that the active constraints in the optimization problem are the average S/I requirements only.

In a CDMA network with N users and M cells, the linear power assignment problem can be formulated as follows.

Find a set of energy per bit values $\{E_{bij}\}$ $i = 1, 2, \dots, N_j$ and $j = 1, 2, \dots, M$ which minimizes the total average transmitted power by all the users in the network that can be calculated as

$$P_{ave} = \sum_{j=1}^M \sum_{i=1}^{N_j} E_{bij} \cdot h_{ij} \cdot \bar{r}_i \quad \text{Eq(6.1)}$$

with the following linear constraints

$$(1) \quad \overline{(S/I)}_{ij} \geq (S/I)_{ij}^+ \quad (i = 1, 2, \dots, N_j) \quad (j = 1, 2, \dots, M) \quad \text{Eq(6.2)}$$

h_{ij} is the path loss encountered by user i in the j^{th} cell, and $\bar{r}_{ij}$ is the average bit rate of the same user. $(S/I)_{ij}$ is the instantaneous signal to interference ratio encountered by user i in cell j . $\overline{(S/I)}_{ij}$ is the average value of $(S/I)_{ij}$, and $(S/I)_{ij}^+$ is the acceptable average signal to interference ratio for the same user.

6.3 Linear power assignment algorithm

In the proposed linear power assignment scheme, each mobile is assigned a target average received power level at the base station that is proportional to its required average signal to interference ratio. In other words

$$P_{target,i} = \Upsilon_{opt,j}^* \cdot \left(\frac{S}{I}\right)_i^+ \cdot \bar{r}_i \quad \text{Eq(6.3)}$$

where $P_{target,i}$, $\Upsilon_{opt,j}^*$, $\bar{r}_i$ are the target average power for the mobile i , the optimum power coefficient at the j^{th} cell, and the average bit rate of the i^{th} mobile in the j^{th} cell respectively.

In this section, the rationale behind this algorithm is addressed. Furthermore, an equation for calculating the value of $\Upsilon_{opt,j}^*$ in terms of the number of mobiles in the cell and their traffic parameters is derived.

Assuming there is a large number of users in the cell ($N_j \rightarrow \infty$), then the average interference experienced by different mobiles at a base station is approximately the same. Denoted by $\bar{I}_j$, the total average interference power at the base station in the j^{th} cell. $\bar{I}_j$ can be calculated as

$$\sigma_j^2 + \sum_{i=1}^{N_j} E_{bij} \cdot h_{ij} \cdot \bar{r}_i \equiv \bar{I}_j \quad j = 1, 2, \dots, M \quad \text{Eq(6.4)}$$

Using this approximation, it is possible to solve the linear power assignment problem and derive a closed form solution for the $\{E_{bij}\}$. After some mathematical manipulation, a general expression for $\{E_{bij}\}$ can be derived as

$$E_{bij} \cdot h_{ij} = \Upsilon_{opt,j}^* \cdot \left(\frac{S}{I}\right)_{ij}^+ \quad j = 1, 2, \dots, M \quad \text{Eq(6.5)}$$

The values of $\{\Upsilon^*_{opt,j}\} \quad j = 1, 2, \dots, M$ can be found by solving the following set of M linear equations (one equation per cell):

$$\Upsilon^*_{opt,j} = \frac{\frac{1}{W} \cdot [\overline{\sigma_j^2} + \sigma_T^2]}{1 - \frac{1}{W} \sum_{i=1}^{N_j} \left(\frac{S}{I}\right)_{ij}^+ \cdot \overline{r_{ij}}} \quad j = 1, 2, \dots, M \quad \text{Eq(6.6)}$$

where $\overline{\sigma_j^2}$ is the average inter-cell interference and σ_T^2 is the background noise at the base station in the j^{th} cell and is assumed to be the same in different cells. $\overline{\sigma_j^2}$ is calculated as:

$$\overline{\sigma_j^2} = \sum_{\substack{k=1 \\ k \neq j}}^M \Upsilon^*_{opt,k} \left[\sum_{i=1}^{N_j} \left(\frac{S}{I}\right)_{ik}^+ \cdot \overline{r_{ik}} \cdot h_{ik}^{(j)} \right]$$

For notational convenience, the following change of variable is introduced: $E^*_{bij} = E_{bij} \cdot h_{ij}$ where E^*_{bij} is the received energy per bit from i^{th} mobile in the j^{th} cell.

The above direct method of calculating $\{\Upsilon^*_{opt,j}\}$ requires a central node for power control which has the complete knowledge of $\{h_{ij}\}$ and $\{h_{ik}^{(j)}\}$ (the attenuation/gains parameter from the mobiles to the base stations in the network).

An iterative algorithm can be used to obtain the values of $\{\Upsilon^*_{opt,j}\}$ based on the measurement of inter-cell interference power in a distributed manner. Using some theorems proved in [107], it can be shown that the following iterative algorithm, which is run independently at each base station, converges to the optimum value of $\{\Upsilon^*_{opt,j}\}$ as the number of iterations tends to the infinity [107].

$$\Upsilon^*_{opt,j}(t_{n+1}) = \frac{\frac{1}{W} \cdot [\overline{\sigma_j^2}(t_n) + \sigma_T^2]}{1 - \frac{1}{W} \sum_{i=1}^{N_j} \left(\frac{S}{I}\right)_{ij}^+ \cdot \overline{r_{ij}}} \quad j = 1, 2, \dots, M \quad \text{Eq(6.7)}$$

where

$$\overline{\sigma_j^2}(t_n) = \sum_{k=1}^M \Upsilon^*_{opt,k}(t_n) \left[\sum_{i=1}^{N_k} \left(\frac{S}{I}\right)_{ik}^+ \cdot \overline{r_{ik}} \cdot h_{ik}^{(j)} \right]$$

t_n represents the time instant for the n^{th} update of power coefficient and $\sigma_k^2(t_n)$ is the value of the inter-cell interference power measured in the k^{th} cell at the n^{th} update instant.

6.3.1 Imperfect power control

The linear power assignment algorithm that was developed in the previous section can be implemented through a closed loop power control mechanism. After determination of the required power level at the cell site, the transmit power of the mobiles can be adjusted by sending appropriate control commands from the base station. Similarly to the provisions of the IS-95 standard, the base station can adjust the transmitter power level by .5 dB periodically every 1.25 ms.

In an outdoor cellular CDMA, despite the implementation of a fast closed loop power control, there will be random fluctuations in the received power level, and the received power levels will differ from target levels. These effects are primarily due to user mobility, lognormal shadowing, and error in the feedback loop of the power control mechanism [100]. The necessary modifications in the linear power assignment algorithm in order to take into consideration the effect of imperfect power control are outlined in this section.

It has been shown that the fluctuation in the received power from a mobile can be modeled by a lognormal distribution [12][100]. Therefore, the users' received energy per bit values under optimum linear power assignment can be calculated as:

$$\widehat{E}_{bij} = \Upsilon_{opt,j}^* \cdot \left(\frac{S}{I}\right)_{ij}^+ \cdot 10^{\frac{\zeta_{ij}}{10}} \quad \text{Eq(6.8)}$$

where $\widehat{E}_{bij}$ is the actual received energy per bit per user at the base station. ζ_{ij} is a zero mean Gaussian random variable, with standard deviation equal to Δ , which has a typical value of $0 \leq \Delta \leq 2$ dB.

The instantaneous and average signal to interference ratios for user i in the j^{th} cell with imperfect power control can be found as

$$(S/I)_{ij} = \frac{E^*_{bij} \cdot 10^{\zeta_{ij}/10} \cdot U_{ij}}{\frac{1}{W} \left[\sigma_j^2 + \sigma_T^2 + \sum_{m=1}^{N_j} E^*_{bmj} \cdot 10^{\zeta_{mj}/10} \cdot R \cdot U_{mj} \right]} \quad \text{Eq(6.9)}$$

$$\overline{(S/I)}_{ij} = \frac{E^*_{bij} \cdot 10^{\overline{\zeta_{ij}/10}}}{\frac{1}{W} \left[\overline{\sigma_j^2} + \sigma_T^2 + \sum_{m=1}^{N_j} E^*_{bmj} \cdot 10^{\overline{\zeta_{mj}/10}} \cdot \overline{r_{mj}} \right]} \quad \text{Eq(6.10)}$$

$i = 1, \dots, N_j \quad j = 1, \dots, M$

The iterative algorithm in Eq(6.7) can be modified as follows to take into account the effect of imperfect power control:

$$\Upsilon^*_{opt,j}(t_{n+1}) = \frac{\frac{1}{W} \cdot [\overline{\sigma_j^2}(t_n) + \sigma_T^2] \cdot 10^{\overline{\zeta/10}}}{1 - \frac{1}{W} 10^{2\overline{\zeta/10}} \sum_{i=1}^{N_j} \left(\frac{S}{I} \right)_{ij}^+ \cdot \overline{r_{ij}}}$$

where

$$\overline{\sigma_j^2}(t_n) = \sum_{\substack{k=1 \\ k \neq j}}^M \Upsilon^*_{opt,k}(t_n) \left[\sum_{i=1}^{N_j} \left(\frac{s}{I} \right)_{ik}^+ \cdot \overline{r_{ij}} \cdot h_{ik}^{(j)} \cdot 10^{\overline{\zeta_{kj}/10}} \right]$$

6.4 Optimum linear power assignment (Simulation results)

A set of simulation experiments were implemented and some numerical calculations were done in order to evaluate the performance of the linear power assignment strategy developed in the previous sections.

Three classes of traffic are considered in the network, including variable rate video, fixed rate video and voice. The number of users in each class is kept fixed during the simulation (no call arrival or departure). All the results are averaged over one thousand realizations of

user locations in the network. The user locations at each trial are assumed to be uniformly distributed over the network area. Furthermore, each user is assumed to belong to each class of traffic with equal probability.

In the first set of simulations, the convergence speed for the linear power assignment is estimated in a sixteen cell network. Results are shown in Fig(6.1). As is shown by these curves, convergence speed decreases as the number of mobiles in the network or their required average S/I increases.

The outage probability and the average S/I for each class of traffic when linear power assignment is implemented as underlying power assignment method are studied, and the results are shown in Figure 6.2. In this experiment, the signal to interference ratio for each user during its connection life time is monitored, and empirical outage probability is estimated. The outage probability is averaged over the users belonging to the same class of traffic. Call duration time is set equal to the simulation time at each trial (no call departure) and is long enough to provide a reliable estimate for the outage probabilities.

It is important to note that outage probabilities increase without any bound as the number of mobiles in the network increases. This observation is the main difference between the linear and non-linear power assignments. In the nonlinear power assignment algorithm, outage requirements for the mobiles were taken into account directly into the power assignment algorithm and the outage probability remained under the acceptable threshold regardless of number of mobiles in the network.

The impact of imperfect power control on the performance of the linear power assignment algorithm is studied and the results are presented in Figures 6.4 to 6.7. Lognormal shadowing with 4 dB standard deviation is considered in these experiments.

From these figures, it can be concluded that the linear power assignment algorithm can converge under imperfect power control scenario. However, both outage probability and convergence speed are affected considerably. Higher outage probability and slower convergence result when imperfect power control is assumed in the simulation.

Figure 6.1: Convergence speed of the linear power assignment algorithm for different values of required average S/I for each class of traffic

Figure 6.2: Outage probability for different classes of traffic under linear power assignment

Average required signal to interference ratios:

Variable rate video: 8.5 dB

Fixed rate video: 7 dB

Voice: 5 dB

Figure 6.3: Outage probability for different class of traffic under linear power assignment (perfect power control)

Average required signal to interference ratios:

Variable rate video: 10 dB

Fixed rate video: 8.5 dB

Voice: 7 dB

Figure 6.4: Convergence speed of the linear power assignment algorithm with imperfect power control

Average required signal to interference ratios for different classes of traffic:

Variable rate video: 8.5 dB

Fixed rate video: 7 dB

Voice: 5 dB

Figure 6.5: Outage probability for different classes of traffic under linear power assignment scheme

(Imperfect power control with 1.5 dB error)

Average required signal to interference ratios for different classes of traffic:

Variable rate video: 8.5 dB

Fixed rate video: 7 dB

Voice: 5 dB

Figure 6.6: Outage probability for different classes of traffic under linear power assignment scheme

(Imperfect power control with 1 dB error)

Average required signal to interference ratios for different classes of traffic:

Variable rate video: 8.5 dB

Fixed rate video: 7 dB

Voice: 5 dB

Figure 6.7: Outage probability for different classes of traffic under linear power assignment scheme

(Imperfect power control with 0.5 dB scheme)

Average required signal to interference ratios for different classes of traffic:

Variable rate video: 8.5 dB

Fixed rate video: 7 dB

Voice: 5 dB

6.5 Mobile admission criteria

In the proposed framework for power management and call admission control, mobiles' power levels are set according to their required average S/I while two layers of admission control regulates the admission of new mobiles to ensure that average S/I and outage requirements in the network are satisfied.

In the first phase of the admission control algorithm, the network management agent should verify the admissibility of a new mobile based on its required average S/I and the state of the existing connections in the network. A mobile is admitted in this phase of admission control if the admission control agent decides that after the arrival of new mobile, linear power assignment algorithm remains feasible.

A second layer of admission control ensures that the outage requirements are satisfied. Outage probability of interference power is estimated at the base station, and a new user is admitted if the estimated outage probability is below an acceptable threshold.

A well defined cell capacity boundary is necessary as part of an admission control algorithm to determine the admissibility of a new mobile. Cell capacity in the context of this thesis is defined as the maximum number of mobiles from each class of traffic that can be admitted in the cell simultaneously while both constraints on average S/I and outage probability for the mobiles in the network are satisfied.

Due to the non-linearity inherent in the outage constraints, a closed form expression for cell capacity boundary in a CDMA wireless network could not be found. In this section, a set of equations are derived that allow us to determine the admissibility of a mobile under the condition that the network is in a feasible state before the arrival of the new mobile. A network is said to be in a feasible state if all the average S/I and outage probability constraints are satisfied.

Because there are two sets of constraints (linear and non-linear) that should be satisfied in the non-linear power assignment problem, two inequalities that jointly determine admissibility of a mobile in a cell are found.

6.5.1 Admission condition with respect to the average constraints

Using the lemma (1) and (2) of Chapter 5, a sufficient condition for the existence of a solution for the linear power assignment problem is derived and is presented in the following sections.

If a CDMA network is feasible with respect to the average constraints, it remains feasible after the arrival of a new mobile, if

$$\overline{\sigma_j^2} + Y_{opt,j}(N) \sum_{i=1}^{N+1} \left(\frac{s}{I} \right)_{ij}^+ \cdot \overline{r_{ij}} + \sigma_T^2 \leq W \cdot \alpha_{Max} \cdot Y_{opt,j}(N) \quad \text{Eq(6.11)}$$

where

$$\alpha_{Max} = \min(\{\alpha_{Max,j}\}) \quad j = 1, 2, \dots, M$$

$\alpha_{Max,j}$ is the maximum average power coefficient for the j^{th} cell (cell of arrival) that determines the maximum ratio the optimum linear power coefficient in that cell ($Y_{opt,j}$) can be increased by, without violating the transmitter power limit. A derivation method for $\alpha_{Max,j}$ is explained in Chapter 5. $Y_{opt,j}(N)$ is the optimum linear power assignment coefficient when there are N mobiles in the j^{th} cell and is derived using the iterative algorithm explained in the previous section. $\overline{\sigma_j^2}$ is the average inter-cell interference power level before arrival of the new mobile.

Proof:

Assume the new mobile which is seeking the connection is the $(N+1)^{th}$ mobile in the j^{th} cell and the linear power assignment coefficient before the arrival of the new mobile is $Y_{opt,j}(N)$.

A sufficient condition for $(\alpha_j \cdot Y_{opt,j}(N))$ to be an upper bound for the linear power assignment coefficient in the j^{th} cell can be found by substituting the E^*_{bij} by $\alpha_j \cdot Y_{opt,j}(N) \cdot \left(\frac{s}{I} \right)^+$ in the average S/I constraint in the j^{th} cell.

By carrying the necessary substitutions in the average S/I constraint in the j^{th} cell, one can show that α_j should satisfy the following inequality:

$$\alpha_j \cdot \Upsilon_{opt,j}(N) \geq \frac{\frac{1}{W} \cdot [\alpha_j \cdot \overline{\sigma_j^2} + \sigma_T^2]}{1 - \frac{1}{W} \sum_{i=1}^{N+1} \left(\frac{S}{I}\right)_{ij}^+ \cdot \overline{r_{ij}}} \quad \text{Eq(6.12)}$$

The reader should note that, $\alpha_j \cdot \overline{\sigma_j^2}$ is an upper bound for the value of average inter-cell interference after the arrival of the new mobile. This can be concluded directly from lemma 1 in Chapter 5 and the proof of lemma 2 in Appendix A.

The minimum value of α_j that satisfies the constraint in Eq(6.12) can be found as:

$$\alpha_j = \frac{\frac{\sigma_T^2}{W}}{\Upsilon_{opt,j}(N) - \frac{1}{W} \overline{\sigma_j^2} - \frac{1}{W} \cdot \Upsilon_{opt,j}(N) \sum_{i=1}^{N+1} \left(\frac{S}{I}\right)_{ij}^+ \cdot \overline{r_{ij}}} \quad \text{Eq(6.13)}$$

If the new mobile is admitted, then $\hat{E}_{bi} = \alpha_j \cdot \Upsilon_{opt,j}(N) \cdot \left(\frac{S}{I}\right)_{ij}^+$ will be an upper bound for the E_{bi}^* resulting from the linear power assignment algorithm.

Based on the above argument it can be concluded that the following condition is a sufficient condition for the existence of a solution for the linear power assignment problem in the network:

$$1 \leq \alpha_j \leq \alpha_{Max} \quad \alpha_{Max} = \min(\{\alpha_{Max,j}\}) \quad j = 1, 2, \dots, M \quad \text{Eq(6.14)}$$

By replacing the value of α_j from equation (6.13) in Eq(6.14), one can derive the expression in equation (6.11).

Therefore, an admission control scheme based on a periodical exchange of $\alpha_{Max,j}$ and using equation (6.11) as a criteria for call admission control will guarantee that after the arrival of a new mobile, the average S/I requirements and transmitter power limits for the mobiles in the network are satisfied.

The formulation of the feasibility condition with respect to the average S/I constraints can be extended to include the effect of imperfect power control.

Assuming the received energy per bit at the base station for the i^{th} mobile is derived according to Eq(6.8), then Eq(6.11) can be modified after some mathematical manipulation to include the effect of imperfect power control as follows

$$\overline{10^{\xi/10}} \cdot \overline{\sigma_k^2} + \Upsilon_{opt,k}(N) \cdot \overline{10^{(2\xi)/10}} \sum_{i=1}^{N+1} \left(\frac{s}{\bar{I}} \right)_i^+ \cdot \bar{r}_i + \overline{10^{\xi/10}} \sigma_T^2 \leq W \cdot \alpha_{Max} \cdot \Upsilon_{opt,k}(N) \quad \text{Eq(6.15)}$$

where

$$\alpha_{Max} = \min(\{\alpha_{Max,j}\}) \quad j = 1, 2, \dots, M$$

Here, $\overline{10^{\xi/10}}$ is the average value of the lognormal random variable that models the fluctuation in the received power due to the imperfect power control.

6.5.2 Admission condition with respect to the outage constraints

In this section, the feasibility condition with respect to the outage constraints is derived, and the underlying assumptions are outlined.

Because a fixed processing gain scheme is adopted in the cell, the instantaneous received power level of user i in the j^{th} cell can be expressed as $(Power)_{ij} = E^*_{bij} \cdot R \cdot U_{ij}$ where U_{ij} is a two value random variable with the following probability density function:

$$f(U_{ij}) = \begin{cases} \frac{\bar{r}_{ij}}{R} = P_{i1} & U_{ij} = 1 \\ 1 - \frac{\bar{r}_{ij}}{R} = P_{i0} & U_{ij} = 0 \end{cases} \quad \text{Eq(6.16)}$$

R is the system transmission rate ($R=144$ Kb/s).

The set of non-linear constraints in the j^{th} cell can be re-written in a manner similar to the Eq(4.7) as follows:

$$\begin{aligned}
& \text{prob}(U_{1j} = 1) \cdot \text{prob} \left(\left[\frac{1}{W} \left[\sigma_j^2 + \sigma_T^2 + \sum_{m=1}^{N+1} E_{bmj}^* \cdot R \cdot U_{mj} \right] \right]^{-1} \leq \frac{(S/I)_1^*}{E_{b1j}^*} \right) \leq L_{1j} \\
& \text{prob}(U_{2j} = 1) \cdot \text{prob} \left(\left[\frac{1}{W} \left[\sigma_j^2 + \sigma_T^2 + \sum_{m=1}^{N+1} E_{bmj}^* \cdot R \cdot U_{mj} \right] \right]^{-1} \leq \frac{(S/I)_2^*}{E_{b2j}^*} \right) \leq L_{2j} \\
& \vdots \\
& \text{prob}(U_{N+1j} = 1) \cdot \text{prob} \left(\left[\frac{1}{W} \left[\sigma_j^2 + \sigma_T^2 + \sum_{m=1}^{N+1} E_{bmj}^* \cdot R \cdot U_{mj} \right] \right]^{-1} \leq \frac{(S/I)_{Nj}^*}{E_{bN+1j}^*} \right) \leq L_{N+1j}.
\end{aligned}$$

The above set of outage constraints (inequalities) in the j^{th} cell can be presented in the following general form:

$$P_{i1} \cdot \left(\text{Prob} \left(I_j^{-1} \leq \frac{(S/I)_{ij}^* / E_{bij}^*}{W} \right) \right) \leq L_{ij} \quad i = 1, 2, \dots, N+1 \quad \text{where} \quad \text{Eq(6.17)}$$

$$I_j = \left[\sigma_j^2 + \sigma_T^2 + \sum_{m=1}^{N+1} E_{bmj}^* \cdot R \cdot U_{mj} \right]$$

Because all the $N+1$ outage constraints are applied on a single random variable I_j , a sufficient condition for the set of $\{E_{bij}^*\}$ to be a feasible solution for the non-linear power assignment problem with respect to the outage constraints can be found by solving the most stringent condition in Eq(6.17). Therefore, a feasibility condition with respect to the outage constraints in the j^{th} cell can be written as

$$P_{\max} \cdot \text{prob} \left((I_j) \geq \left(\frac{W}{\beta_{\max, j}} \right) \right) \leq L \quad \text{Eq(6.18)}$$

where $P_{\max} = \max\{P_{i1}\}$ for $i = 1, 2, \dots, N+1$ and

$$\widehat{\beta}_{max,j} = \max \left\{ \frac{(S/I)^*_{ij}}{E^*_{bi}} \right\} \quad i = 1, 2, \dots, N+1$$

$$L = \min \{L_{ij}\} \quad i = 1, 2, \dots, N+1$$

Assuming that the linear power assignment is implemented as the underlying power assignment method, the expression in Eq(6.18) can be written in terms of the linear power assignment coefficients ($\Upsilon_{opt,j} \quad j = 1, 2, \dots, M$). By substituting the E^*_{bij} in Eq(6.17) with the value derived from the linear power assignment algorithm as

$$E^*_{bij} = \Upsilon_{opt,j}(N+1) \cdot \left(\frac{S}{I}\right)^+_{ij} \quad \text{Eq(6.19)}$$

Eq(6.18) can be rewritten as

$$P_{max} \cdot \text{prob} \left(I_j \geq \frac{W}{\beta_{max,j}} \cdot \Upsilon_{opt,j}(N+1) \right) \leq L_{ij} \quad \text{Eq(6.20)}$$

where

$$\beta_{max,j} = \max \{ \beta_{ij} \} \quad i = 1, 2, \dots, N+1$$

$$\beta_{ij} = \frac{(S/I)^*_{ij}}{(S/I)^+_{ij}}$$

$$\text{and } I_j = \left[\sigma_j^2 + \sigma_T^2 + \Upsilon_{opt,j}(N+1) \sum_{m=1}^{N+1} \left(\frac{S}{I}\right)^+_{ij} \cdot R \cdot U_m \right]$$

It should be noted that if $\beta_{max,j}$ and L do not correspond to the same class of traffic, then a call admission control based on Eq(6.20) can be a conservative scheme. However, in most practical cases it is reasonable to assume that the traffic class with the largest β_{ij} (outage margin) has the smallest outage threshold (L_{ij}) as well.

Without loss of generality, in the rest of the thesis it has been assumed that the required outage thresholds are equal for different classes of traffic, $L_1 = L_2 = \dots = L_N = L$.

Furthermore, we limited the scope of our investigation to the cases where $\{\beta_{ij}\}$ are equal for different mobiles in the same cell. The common value of $\{\beta_{ij}\}$ in the j^{th} cell is denoted by β_j .

Following a similar method used for developing the feasibility condition with respect to the average S/I constraints, a modified outage condition that includes the effect of imperfect power control can be found as

$$P_{max} \cdot \text{prob}\left(10^{\xi/10} \cdot \widehat{I}_j \geq \frac{W}{\beta_{max,j}} \cdot \Upsilon_{opt,j}(N+1)\right) \leq L_{ij}$$

where

Eq(6.21)

$$\widehat{I}_j = \sigma_j^2 + \sigma_T^2 + \Upsilon_{opt,j}(N+1) \sum_{m=1}^{N+1} \left(\frac{S}{I}\right)_{ij}^+ \cdot 10^{\xi_{ij}/10} \cdot R \cdot U_m$$

In the second layer of the proposed admission control framework, a linear estimator is used to predict the outage probability in Eq(6.20). If the inequality in Eq(6.20) remains valid in the j^{th} cell based on the predicted outage probability, then the new mobile will be admitted in the cell. The prediction method and the admission control scheme are addressed in the next chapter.

6.6 Tele-traffic model of a base station in a CDMA cell

In this section a tele-traffic model for a cell site that supports multimedia traffic is developed. The main goal in developing this model is to create an abstract model that reflects the underlying system constraints due to the power control and the transmission scheme adopted at the lower layers. Furthermore, a tele-traffic model provides enough information for the system manager agent at the network layer to make a decision on the admission of a new mobile.

The traffic model for the CDMA base station is specifically developed to capture and model the behavior of the system around its saturation state where the arrival of a new user to the cell might degrade the performance of other users' communication links beyond their acceptable threshold. The feasibility conditions for outage and average constraints developed in the previous sections express a relationship between traffic parameters and the cell capacity and are the basis of the tele-traffic model presented in this chapter.

6.6.1 CDMA cell site's model

The closest counterpart in the world of wired networks to a cellular CDMA base station is an unbuffered ATM switch employing statistical multiplexing. There are considerable functional similarities between the two architectures. However, there are many fundamental differences as well.

In an unbuffered ATM switch, "C" channels are shared by independent heterogeneous sources where each source requires a fixed or variable number of channels. Because there is no queue, overflow happens when the aggregate bit rate of the arriving traffic exceeds the capacity of the server.

The overflow condition for an unbuffered ATM switch supporting total of N users can be stated as follows:

An ATM switch is in state of overflow if $\sum_{i=1}^N C_i(t) \geq C$ where $C_i(t)$ is the capacity demand at time " t " from user i .

By comparing this equation with outage and average feasibility conditions in a CDMA cell, a tele-traffic model can be built for a CDMA cell supporting multimedia traffic.

The following dual relationships exist between the two models.

(1) User power at the base station is similar to the user bit rate in an ATM switch. An overflow event happens when the total interference power exceeds a threshold.

Due to the imperfect power control, users' power levels are not known at the time of the connection request and the statistics of the user power can change during the lifetime of a connection because of random changes in the environment. This is one of the main differences between an ATM switch and a multimedia CDMA base station.

(2) The interference limit is equivalent to the cell capacity "C" in ATM switch. Due to the inter-cell interference, the system has a random and time variant capacity.

Because there are two feasibility conditions that must be satisfied in order to guarantee the required quality of service by the users, the CDMA cell site is modeled as a combination of two servers with different capacities. One corresponds to the average condition and the other one to the outage condition. The model for a CDMA cell with linear power assignment is shown in Figure 6.8.

Call admission control is based on the model developed for the CDMA cell site and requires a two fold approach. A deterministic algorithm decides upon the admissibility in the average server while the outage sever requires a probabilistic approach to determine the availability of the resources. A new user joins the cell if it finds enough resources at both servers. The access control algorithm is the subject of the next chapter.

Figure 6.8: Tele-traffic model for CDMA cell with optimum linear power control

6.7 Cell capacity as a function of Q-Vector

The main goal of this section is to demonstrate the relationship between the required S/I values and the cell capacity boundary when the linear power assignment algorithm is employed. It is shown in this section that the value of the Q-vector will affect the capacity boundary in terms of both its geometrical shape and its values.

In order to make the numerical analysis tractable, the scope of the analysis is limited to the capacity of a CDMA cell in the absence of inter-cell interference and with perfect power control. Under these assumptions, a closed form expression for outage constraints that allows us to estimate the cell capacity numerically can be found.

The outage constraints in Eq(6.20) with perfect power control and in the absence of inter-cell interference in a cell can be simplified as

$$Prob(U_i = 1) \cdot \sum_S \prod_{i=1}^{NC} \left[\binom{N_i}{K_i} (P_{i,1})^{K_i} (P_{i,0})^{N_i - K_i} \right] \leq L \text{ for } i = 1, 2, \dots, NC \quad \text{Eq(6.22)}$$

where

$$S = \left\{ K_i: \text{ such that } \left(\sigma_T^2 + \Upsilon_{opt}(N) \sum_{i=1}^{NC} K_i \cdot \left(\frac{S}{I} \right)_i^+ \cdot R \right) \geq \frac{W \Upsilon_{opt}(N)}{\beta} \right\}$$

where NC is the number of traffic classes in the cell, and N_i is the number of users that belong to class i . N is the total number of users in the cell.

$$N = \sum_{i=1}^{NC} N_i \quad \text{Eq(6.23)}$$

$P_{i,1}$ is the probability that user i is active, and $P_{i,0}$ is the probability that the same user is idle

$$P_{i,1} = \frac{\bar{r}_i}{R} ; \quad P_{i,0} = 1 - P_{i,1} \quad \text{and } \beta = \frac{(S/I)^*_i}{(S/I)_i^+} \quad (i = 1, 2, \dots, N) \text{ is the outage}$$

ratio, which is assumed to be the same for the mobiles in the cell.

The rest of the parameters are defined in the previous sections and can be found in the list of symbols as well.

The inequality in Eq(6.22) is derived based on the assumption that the total interference power has a binomial probability distribution. This assumption is justified because the fixed processing gain scheme is adopted as the underlying transmission method. This issue was discussed in more detail in Chapter 4.

The limit on the number of admissible mobiles due to the average constraints can be found from the following expression:

$$\sigma_T^2 + \Upsilon_{opt}(N) \sum_{i=1}^{NC} N_i \cdot \left(\frac{S}{I}\right)_i^+ \leq W \cdot \Upsilon_{opt}(N) \cdot \alpha_{max} \quad \text{Eq(6.24)}$$

Eq(6.24) is derived from Eq(6.11) with the assumption that inter-cell interference is zero.

The maximum number of mobiles from each class of traffic that can be supported simultaneously in a cell and satisfy the constraints expressed in Eq(6.22) and Eq(6.24) are found through an exhaustive numerical search. Results for different sets of Q-vectors are shown in Figures 6.9 to 6.11. In these results, transmitter maximum power limit is not considered.

An important conclusion that can be drawn from these capacity limit surfaces is that they are approximately a plane surface. Furthermore, as the values of the required signal to interference ratios decrease, the limiting surfaces tend to plane surfaces.

The above observation leads to the conclusion that access control based on the equivalent bandwidth technique [42] can be effective for multimedia CDMA call admission control. The equivalent bandwidth technique, is based on approximating the capacity boundary with a hyper-plane and carrying out the call admission control accordingly [20]. It may perform satisfactorily when the call boundary is a hyper-plane [20].

Figure 6.9: Cell capacity boundary (Maximum number of mobiles from each class of traffic)

Required Q-vectors:

Variable rate video: [13.5dB,11.5dB,.001]

Fixed rate video : [11.5dB,9.5dB,.001]

Voice : [9.5dB,7.5dB,.001]

Figure 6.10: Cell capacity boundary (Maximum number of mobiles from each class of traffic)

Required Q-vectors:

Variable rate video: [11.5dB,9.5dB,.001]

Fixed rate video : [9.5dB,7.5dB,.001]

Voice : [7.5dB,5.5dB,.001]

Figure 6.11: Cell capacity boundary (Maximum number of mobiles from each class of traffic)

Required Q-vectors:

Variable rate video: [9.5dB,7.5dB,.001]

Fixed rate video : [7.5dB,5.5dB,.001]

Voice : [5.5dB,3.5dB,.001]

6.8 Conclusion

A linear power assignment algorithm is introduced and developed in this chapter. The main advantage of this algorithm is its simplicity and robustness compare to the non-linear power assignment method. However, the linear power assignment is a sub-optimum scheme in utilizing the cell capacity.

The effect of imperfect power control on the performance of the linear power assignment algorithm is formulated using some simple assumptions that allowed us to find a closed form expression for the average S/I.

Our findings show that the larger the variance of error in the power assignment, the higher the overload probability, and the slower the convergence speed of the linear power assignment algorithm will be.

Because power control error is an unpredictable phenomenon, and its value is not known to the base station at the time of connection and changes during the connection's life time, it poses a significant challenge for any access control agent.

The cell capacity equations for a CDMA cell supporting multimedia traffic are found and formulated in this chapter. The geometrical shape of the cell boundary was found to be close to a hyper-plane. These results suggest that an admission control method based on the equivalent bandwidth theory might be effective in regulating the admission of new mobiles. This issue is investigated further in the next chapter.

Chapter 7

Adaptive access Control for multimedia CDMA networks

7.1 Introduction

In order to provide guaranteed quality of service in a multimedia CDMA network, it is necessary to regulate the admission of users. An access control scheme will accept or reject a new connection request based on the present state of the traffic in the cell and a prediction of the future consequences of admitting a new call.

Assessment of occupied capacity and estimation of the future capacity requirement in the average server in the cell site model, which is presented in Figure 6.8, can be done in a deterministic way. However, due to the statistical variations involved in cell capacity and user power level, a statistically predictive algorithm is needed to manage the access control at the outage server.

The main focus of this chapter is on the development of an access algorithm for the outage server; the average server requirement is considered implicitly.

The cell capacity boundary in a multimedia CDMA is approximately a hyper-plane, as was noted in previous chapters. The equivalent bandwidth technique, a recently developed access control scheme for broadband ATM networks, is known to be efficient for cases where the admission boundary is approximately a hyper-plane [67]. In this chapter, the effectiveness of the equivalent bandwidth technique for access control in multimedia CDMA wireless networks is investigated, and its advantages and limits are determined.

A novel two level access control strategy based on a modified equivalent bandwidth technique is proposed and its performance is compared with the standard equivalent bandwidth algorithm.

In order to highlight the main aspects of the proposed access scheme clearly, in the first part of this chapter, a single cell scenario (no inter cell interference) is considered. The effect of inter-cell interference on the proposed access control algorithm is addressed in section 7.16.

7.2 Access control for multimedia CDMA networks based on equivalent bandwidth technique

Admission control based on the equivalent bandwidth technique primarily uses the Chernoff bound for the overload probability [19][67]. A set of control parameters for the traffic sources is calculated based on the Chernoff bound that allows a circuit switching type of admission control. This technique is outlined in the following sections. Some background material on the theory of equivalent bandwidth is provided in Appendix C.

Denoted by $\widehat{I}$, the intra-cell interference in a single cell CDMA, $\widehat{I}$ can be found using the following equation:

$$\widehat{I} = \sum_{i=1}^N E^*_{b_i} \cdot 10^{\frac{\zeta_i}{10}} \cdot R \cdot U_i \quad \text{Eq(7.1)}$$

where $E^*_{b_i}$ is the received energy per bit for the i^{th} mobile. Assuming that the linear power assignment algorithm is implemented in the cell, then $E^*_{b_i} = \Upsilon_{opt} \cdot \left(\frac{S}{I}\right)^+_i$.

The admission condition with respect to the outage constraint in a single cell CDMA can be simplified as

$$Prob\left(\widehat{I} \geq \frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2\right) \leq L \quad \text{Eq(7.2)}$$

where L is the overload probability (The effect of users's activity ratio is included in L).

Assuming $V_i = E^*_{b_i} \cdot 10^{\frac{\zeta_i}{10}} \cdot U_i$ ($i=1,2,\dots,N$) are independent random variables (approximately) where U_i is the activity ratio for the user i , then the Chernoff bound for outage probability in the cell can be calculated as

$$Prob\left(\widehat{I} \geq \frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2\right) \leq \exp(-F_K(s^*)) \quad \text{Eq(7.3)}$$

where

$$F_K(s) = s\left(\frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2\right) - \sum_{i=1}^3 K_i \cdot \log M_i(s) \quad \text{Eq(7.4)}$$

and

$$F_{\mathbf{K}}(s^*) = \sup_{s \geq 0} F_{\mathbf{K}}(s) \quad \text{Eq(7.5)}$$

$\mathbf{K}$ is the active user vector $\mathbf{K} = [K_1 \ K_2 \ K_3]$ where K_i is the number of mobiles in the cell that belong to the i^{th} class of traffic. $M_i(s)$ is the moment generating function for type i traffic and is defined by:

$$M_i(s) = E \left[\exp \left(s E_{b_i}^* \left(10^{\frac{\xi_i}{10}} \cdot R \cdot U_i \right) \right) \right] \quad \text{Eq(7.6)}$$

where $E[x]$ is the expected value of x .

The value of s^* can be found based on the asymptotic large deviation approximation [105] using the following equation:

$$F_{\mathbf{K}_{max}}(s^*) = \log \left(\frac{1}{L} \right) \quad \text{Eq(7.7)}$$

where $\mathbf{K}_{max}$ is the maximum user vector whose i^{th} element equals the maximum admissible number of mobiles in the cell from class i traffic. The reader should note that the $E[\cdot]$ in the moment generating function $M_i(s)$ is taken with respect to both U_i and ξ_i . Therefore, this model will take into account the fluctuation in the total received interference power level due to the bit rate variation and imperfect power control.

Because the regular moment generating function for the lognormal distribution can not be defined, we used a modified moment generating function by fixing the upper limit of the moment generating function integral at an appropriate value to calculate M_i . This method of calculating the moment generating function for a log normal distribution was proposed in [101].

The Chernoff upper bound defines a decision area $\tilde{S}$ where

$$\tilde{S} = \{ \mathbf{K} : \text{where } \exp(-F_{\mathbf{K}}(s^*)) \leq L \}$$

Then for $\mathbf{K} \in \tilde{S}$, the outage probability will be bounded above by L .

The equation of a tangent hyper-plane of the decision boundary can be derived as [20]

$$K \cdot e^* = \frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.8)}$$

e_i^* the i^{th} elements of vector e^* can be calculated as [20]

$$e_i^* = \frac{\log M_i(s^*)}{s^* + \left(\log(L) / \left(\frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2 \right) \right)} \quad \text{Eq(7.9)}$$

Because the admission boundary is a concave surface [42], the following condition guarantees that the overload probability remains below the target value of L .

$$K \cdot e^* \leq \frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.10)}$$

The vector e^* is called the equivalent bandwidth vector.

Based on the principle of equivalent bandwidth technique, a new call is admitted if

$$\sum_{i=1}^3 K_i \cdot e_i^* \leq \frac{W\Upsilon_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.11)}$$

7.3 Simulation and Numerical results

Applicability of equivalent bandwidth technique is investigated through simulation experiments.

A basic requirement of the equivalent bandwidth technique is the existence of a positive solution for Eq(7.7) (the Chernoff optimization equation). This condition guarantees that the equivalent bandwidth indices are positive.

The value of (s^*) , the optimum root of Eq(7.7), as a function of traffic parameters is found numerically, and the results are presented in Figures 7.1 and 7.2.

An example of the variation of s^* as a function of traffic parameters is shown in Figure 7.1. Values of s^* for different minimum required signal to interference ratios and activity ratios of traffic sources are found and are plotted in Figure 7.1. In this experiment, a

CDMA cell with a single class of ON-OFF traffic is considered. Power control is assumed to be imperfect, with 2dB error, and the outage probability threshold is set equal to 10^{-6} .

Under a similar assumption of a single class of ON-OFF traffic, operating regions where s^* has positive values are determined, and results in terms of minimum required signal to interference ratios and activity ratios are shown in Figure 7.2. The area under each curve is the operating region for the given outage probability threshold.

The admission boundary, defined as the maximum number of admissible users from each class of traffic, are found for multimedia traffic with different outage probability requirements. It is assumed that the equivalent bandwidth technique is used as the admission control method. Results are shown in Figures 7.3 to 7.5.

The blocking probability versus traffic intensity is determined by simulation, and the result is shown in Figure 7.6. The equivalent bandwidth index for each class of traffic was calculated using equation (7.9), and admission control was carried out based on the sum of the indices according to the criteria expressed in equation (7.11). The outage probability threshold was set at .001, and imperfect power control with 2dB standard deviation is considered.

From these set of figures, one can conclude that call admission control based on the equivalent bandwidth technique is a conservative scheme. This conclusion is based on the fact that equivalent bandwidth indices are calculated based on the Chernoff bound and large deviation approximation. These techniques were originally developed for systems with large capacity and small overflow, in the range of $(10^{-6}-10^{-9})$. The admission boundary changed very little despite the increase in outage probability from 10^{-6} to 10^{-3} , as was shown in Figures 7.3 to 7.5. This observation is due to the restriction in applying equivalent bandwidth technique in systems with small or moderate capacity and high outage probability.

It is evident from Figures 7.1 and 7.2 that the Chernoff bound equation does not have a solution for a wide range of traffic parameters; this fact limits its application even more.

Figure 7.1: Value of optimum root for Chernoff equation versus traffic parameters

Figure 7.2: Operating region (s^* has positive value) versus activity ratio and minimum required signal to interference ratios

Figure 7.3: Admission boundary for access control based on equivalent bandwidth theory

Q-Vectors:

Variable rate video :[9 dB 7.5 dB .001]

Fixed rate video :[7 dB 5.5 dB .001]

Voice :[5.5 dB 4 dB .001]

Figure 7.4: Admission boundary for access control based on equivalent bandwidth theory

Q-Vectors:

Variable rate video :[9 dB 7.5 dB .0001]

Fixed rate video :[7 dB 5.5 dB .0001]

Voice :[5.5 dB 4 dB .0001]

Figure 7.5: Admission boundary for access control based on equivalent bandwidth theory

Q-Vectors:

Variable rate video :[9 dB 7.5 dB .000001]

Fixed rate video :[7 dB 5.5 dB .000001]

Voice :[5.5 dB 4 dB .000001]

Figure 7.6: Blocking probability versus traffic intensity using equivalent bandwidth algorithm

7.4 Adaptive Equivalent bandwidth

Bandwidth efficiency for an access control technique is the most important requirement in a wireless medium with limited available bandwidth.

A control method based on the theory of equivalent bandwidth is modified in a way that makes it applicable for access control in a CDMA cell while keeping the simplicity that is inherent in the equivalent bandwidth approach. In the proposed modified algorithm, admission control is carried out according to the equivalent bandwidth technique principle; however, we suggest modifying the value of the equivalent bandwidth indices periodically, based on the interference power measurement, in order to improve bandwidth utilization.

Denoted by $f_{\mathbf{K}}(t)$, the empirical distribution of interference power given the active user vector $\mathbf{K}$ and by $MRC(L)$ (Minimum Required Capacity), the L^{th} percentile of $f_{\mathbf{K}}(t)$. $MRC(L)$ can be calculated as

$$MRC = \min\{C\} \quad \text{such that} \quad \left[\int_C^\infty f_{\mathbf{K}}(t) \leq L \right] \quad \text{Eq(7.12)}$$

In the proposed adaptive equivalent bandwidth technique, the value of $MRC(L)$ is estimated by periodical measurement of interference power distribution every T seconds. A gradient descent algorithm is used to minimize the difference between the measured $MRC(L)$ and the estimated value derived from the equivalent bandwidth theory.

$$\mathbf{E}_{t_{n+1}} = \mathbf{E}_{t_n} + \beta \cdot \text{error} \cdot \mathbf{K}_{t_n} \quad \text{Eq(7.13)}$$

Where $\text{error} = (MRC(L) - (\mathbf{K}_{t_n} \cdot \mathbf{E}_{t_n}))$,

$\mathbf{E}_{t_n} = [e_1 \ e_2 \ e_3]$ is the equivalent bandwidth vector at time t_n , and β is the adaptation coefficient.

It can easily be shown that adaptive equivalent bandwidth indices after convergence are the coefficients of an optimum linear estimator for $MRC(L)$. In other words, the adaptive equivalent bandwidth vector is the solution of the following minimization problem:

$$\min \left\{ E_K [(MRC(L) - (K \cdot e))^2] \right\} \quad \text{Eq(7.14)}$$

where E_K is the expectation operator with respect to the active user vector. Some analytical insight is provided on the relationships among the equivalent bandwidth indices and the traffic parameters in section 7.10.

An admission control algorithm based on adaptive equivalent bandwidth technique is summarized with the help of a flowchart on the next page.

Adaptive admission control (flow chart)

7.5 Empirical estimation of outage probability in a CDMA cell supporting multimedia traffic

In this thesis, a communication link's performance is characterized by two performance indices, namely, average S/I and outage probability. Therefore, an accurate estimation of these indices is required to be available at the base station as part of the admission control policy. Measurement of average S/I at the base station is not a challenging task due to its deterministic nature; however, estimating outage probability in a multimedia scenario requires a more sophisticated approach.

In this section, the problem of estimating the outage probability for interference power distribution in a CDMA cell with multimedia traffic is addressed. This problem is reformulated in a form more suitable of estimating the L^{th} percentile of the interference power distribution (where L is a target outage probability) instead of directly estimating the outage probability. Although estimating the outage probability or an L^{th} percentile are mathematically equivalent problems, the later is a more suitable measure for the adaptive call admission control problem.

Some background material on the subject, along with a comparative study results, is provided in this section. Existing methods in estimating the L^{th} percentile of the interference power distribution in a CDMA cell are compared, and their suitability is evaluated.

Calculating the L^{th} percentile of interference power distribution for a given number of users in a cell requires the estimation of the empirical distribution of total interference power at the base station.

There is a vast literature on density estimation methods. Reference [83] offers a comprehensive treatment of the theoretical aspects of the subject, and [5][86] provide surveys and bibliography. In this section, a brief summary of the main methods for univariate density estimation is presented. A case study has been conducted to decide on the suitability of these estimation methods in estimating the L^{th} percentile of interference power distribution.

In general, density estimation can be classified either as parametric or non-parametric. In the parametric approach, a distribution model is assumed for the observed data samples while in the non-parametric methods, less rigid assumptions are made about the distribution of the observed data. In non-parametric approach, the only assumption is that

the distribution has a probability density $f(t)$, and the data themselves will determine the estimate of $f(t)$.

7.6 Parametric approach

The Gaussian model is the prime candidate from parametric family of techniques for modeling the interference power distribution in a CDMA environment [92]. The Gaussian approximation for a probability density function of interference power, requires estimating only the empirical mean and variance of the observed data. Another class of density estimators relies on higher statistics estimation using moment matching techniques. One example of this class of estimator is reported in [102]. The main drawback of the higher statistics approach stems from the fact that it requires considerable detailed information about each user's traffic distribution that is not readily available in practical situations. Considering this fact and the general complexity inherent in estimating higher order statistics, only the Gaussian approach from the parametric family of the density estimators is considered in our case study.

7.6.1 Gaussian model

The L^{th} percentile of the interference power can be estimated by modeling the probability distribution of the observed data (total interference power samples) by a Gaussian distribution.

Estimating the L^{th} percentile requires the measurement of the mean value m and the standard deviation σ of the observed data. The L^{th} percentile of interference power distribution can be calculated as

$$MRC(L) = \sqrt{2}\sigma[Q^{-1}(L)] + m \quad \text{Eq(7.15)}$$

where $Q^{-1}(\cdot)$ is the inverse Q-function.

The main advantage of the Gaussian approach is its simplicity. However, because the mobiles' transmitted power random variables are not identically distributed in a multimedia scenario (having different mean and variance) the Gaussian approximation for interference power distribution is not justifiable in general, and can underestimate or overestimate the L^{th} percentile value considerably.

The central limit theorem implies that the interference power distribution will tend towards the Gaussian distribution near the center of its distribution if there are a large

number of mobiles in the cell. However, convergence may be slow at the tails [92]. It is the extreme values of interference that lead to outages.

7.7 Non-parametric technique

The oldest and most widely used non-parametric density estimator is the histogram. For the presentation and exploration of data, histograms are useful. However, due to the fact that the choice of origin and bin width has a significant impact on the accuracy of a histogram in estimating a probability density function, the histogram's applicability is limited. Another disadvantage of a histogram is the inherent discontinuity which make it unsuitable for estimating continuous probability density functions.

Among the non-parametric techniques suitable for estimating a continuous probability density function, the Kernel estimator and the nearest neighbor techniques are considered in the case study [52][90]. They have been chosen because they are less demanding computationally than techniques such as orthogonal series estimation [11] and maximum penalized likelihood estimators [30]. Complexity is an important concern because the estimator is part of the real-time admission control algorithm.

7.7.1 k^{th} Nearest neighbor method

The k^{th} nearest neighbor density estimate at a point " t " is calculated as $\hat{f}(t) = \frac{(k-1)}{2n \cdot d_k(t)}$ where $d_1(t) \leq d_2(t) \leq \dots \leq d_n(t)$ are the distances from the observation point " t " to the sample points arranged in ascending order, and $\hat{f}(t)$ is the estimated probability density function.

The main principle of the k^{th} nearest neighbor density estimate method is based on the following intuition:

Find the k nearest sample points around the point " t ", and denote the interval that spans all the entire k samples by $[t - d_k(t), t + d_k(t)]$. Assuming that the observed samples have a probability density function of $f(t)$, then out of a sample size of n , one would expect that $2r \cdot n \cdot f(t)$ observations to fall in the interval $[t - r \quad t + r]$ for each $r > 0$.

Because, by the definition of the nearest neighbor estimator, exactly $(k-1)$ observations fall in the interval, $[t - d_k(t), t + d_k(t)]$ an estimate of $f(t)$ denoted by $\hat{f}(t)$ may be obtained by putting $(k-1) = 2 \cdot d_k(t) \cdot n \cdot \hat{f}(t)$. This equation can be rearranged to give the definition of the k^{th} nearest neighbor estimate.

It has been shown that the tail of $\hat{f}(t)$ will decay at rate t^{-1} [90], in other words relatively slowly. Therefore, one can expect that the L^{th} percentile derived based on the nearest neighbor method to be a conservative estimate.

7.7.2 Kernel estimator technique

The kernel estimator with kernel K for a density function $f(t)$ is defined by

$$\hat{f}(t) = \frac{1}{nh} \cdot \sum_{i=1}^n K\left(\frac{t - X_i}{h}\right) \quad \text{Eq(7.16)}$$

where X_i s are sample points, and h is called kernel bandwidth. K is a positive value function that satisfies the condition:

$$\int_{-\infty}^{\infty} K(x) \cdot dx = 1 \quad \text{Eq(7.17)}$$

Selection of the kernel function K and the bandwidth parameter h determines the kernel estimator completely.

7.7.3 Ideal kernel

The effectiveness of a density estimator usually is measured by the so called mean integrated square error (*MISE*), which is defined as

$$MISE(\hat{f}) = E\left[\int \{\hat{f}(x) - f(x)\}^2 dx\right] \quad \text{Eq(7.18)}$$

where $f(x)$ is the PDF that is needed to be estimated, and $\hat{f}(x)$ is the estimated PDF.

For a fixed bandwidth parameter, by restricting the kernel function to those functions that are probability density functions themselves, it can be shown that the Epanechnikov kernel has the minimum MSE among the classes of kernels that satisfy the following conditions [90]:

$$\int K(t) dt = 1 \quad \int tK(t) dt = 0 \quad \int t^2 K(t) dt = k_2 \neq 0 \quad \text{Eq(7.19)}$$

The Epanechnikov kernel is defined as

$$K_e(t) = \begin{cases} \frac{3}{4\sqrt{5}} \left(1 - \frac{1}{5}t^2\right) & -\sqrt{5} \leq t \leq \sqrt{5} \\ 0 & \text{otherwise} \end{cases}$$

In Table 7.1, the efficiency (ratio of *MISE* for a kernel function to the value of *MISE* for the Epanechnikov kernel) with respect to the Epanechnikov kernel for several well known functions are summarized.

Table 7.1:

Kernel	K(t)	Efficiency
Epanechnikov	$\frac{3}{4} \left(\left(1 - \frac{1}{5}t^2\right) / (\sqrt{5}) \right)$ for $ t \leq \sqrt{5}$ 0 otherwise	1
Biweight	$\frac{15}{16}(1-t^2)^2$ for $ t \leq 1$ 0 otherwise	.9939
Triangular	$1 - t $ for $ t \leq 1$ 0 otherwise	.9859

Table 7.1:

Kernel	K(t)	Efficiency
Gaussian	$\frac{1}{\sqrt{2\pi}} e^{-\left(\frac{1}{2}\right) \cdot t^2}$	.9512
Rectangular	$\begin{aligned} &\frac{1}{2} \quad \text{for } t \leq 1 \\ &0 \quad \text{otherwise} \end{aligned}$	.9295

Based on Table 7.1, it can be concluded that the efficiency is approximately the same for the above listed functions and other consideration should be taken into account for selecting the kernel function.

Because density estimation is to be used as part of a real-time access control algorithm, computational complexity is a major concern. Direct use of Eq(7.16) for computation of the kernel estimate is highly inefficient. Note however, the kernel estimate is a convolution of the data with the kernel function. It is faster to use the Fourier transform to find the direct and inverse Fourier transforms [91]. Additional simplification will be achieved should one use a kernel that has an explicit closed form Fourier transform that can be used in the calculation of the Fourier transform.

Based on the computational complexity factor, the Gaussian kernel is considered in the simulation experiments, due to the existence of a closed form Fourier transform for the Gaussian function.

7.7.4 Ideal Bandwidth

Two methods are suggested for choosing the bandwidth parameter [90]:

- (a) Reference to a standard distribution
- (b) Least squares cross-validation

In the first method, an optimal value for h is calculated that minimizes MISE for an assumed distribution of the observed data [90].

Least squares cross-validation is a more elaborate technique than the first approach and was suggested in [8]. Given any estimator $\hat{f}$ of a density f , the integrated squared-error can be written as

$$\int (\hat{f} - f)^2 = \int \hat{f}^2 - 2 \int \hat{f} \cdot f + \int f^2 \quad \text{Eq(7.20)}$$

The basic principle of least squares cross-validation is to construct an estimate of $R(\hat{f})$, defined as $R(\hat{f}) = \int \hat{f}^2 - 2 \int \hat{f} f$, directly from the data themselves and to minimize this estimation over h (the bandwidth) to derive the choice of bandwidth.

The main objective in this thesis is to use a functional of estimated density (the L^{th} percentile), not the density estimation itself. It has been suggested that the choice of bandwidth in finding the value of a functional of estimated density is not as sensitive as it is for the density estimate itself [90]. A simple equation was suggested in [90] for calculating the optimum bandwidth parameter in terms of the standard deviation of observed data and the number of observed points, as follows:

$$h_{opt} = 9\sigma \cdot n^{-\frac{1}{5}} \quad \text{Eq(7.21)}$$

where σ is the empirical standard deviation of the observed data and n is the total number of observed points. Considering the complexity involved in the cross-validation approach, equation (7.21) is used to calculate the optimum bandwidth in the simulations carried out in the case study.

7.8 Case study (Simulation results)

A set of simulation experiments is conducted to investigate the relative performance of the methods mentioned in the previous sections in determining the L^{th} percentile of the interference power distribution. The overload probability is set at .001; the related L^{th} percentile is estimated ($L=.001$) by the density estimation technique; and the result of estimations are compared with the actual L^{th} percentile derived using a very high resolution (narrow bin) histogram in the simulation.

The first set of experiments is aimed at homogeneous traffic. The L^{th} percentile is estimated for a different number of users in the cell with a single type of ON-OFF Markovian traffic with residency time of 1.2 second in the ON state and 1.8 second in the OFF state. It is assumed that each source occupies one unit of capacity when it is in the ON state. The results are shown in Figure 7.7.

The extension of this experiment to heterogeneous traffic is carried out. Two types of ON-OFF traffic with different activity ratios (1.2 second and 1.8 second residency time in ON state and 1.8 and 1.2 second residency time in OFF state respectively) are considered. The capacity requirement is kept homogeneous, i.e, one unit of capacity is assumed to be occupied by each source at the ON state. The results are shown in Figure 7.8.

Another set of simulation experiments are conducted based on the multimedia scenario considered in this thesis. Multimedia traffic (Voice + Fixed rate video + Variable rate video) is simulated, and the results are presented in Figure 7.9. In this experiment, an equal number of users from each class of traffic is assumed.

In a practical multimedia CDMA scenario, the distribution of the number of users from different classes of traffic is not homogeneous. For example, it is likely that the number of active video connections are much less than the number of voice connections. For two hypothetical un-symmetrical distributions of numbers of users, the performance of density estimators are compared, and the results are shown in Figures 7.10 and 7.11.

Based on this case study, one can conclude that the kernel estimator for a wide range of traffic scenarios is a reliable technique for estimating the L^{th} percentile. The Gaussian estimation method (parametric estimator) performance was comparable when there was an equal number of users per class in the cell. The kernel estimator is more complex than the Gaussian method, but, as pointed out, it can be implemented using a DSP algorithm. Considering the recent reductions in pricing of DSP processors, employing a kernel estimator as part of the access control algorithm can be well justified.

Figure 7.7: L^{th} percentile estimation for a single class of ON-OFF traffic

Figure 7.8: L^{th} percentile Estimation for two classes of ON-OFF sources

Figure 7.9: Multimedia traffic with imperfect power control (2 dB error)

Q-vectors:

Variable rate video: [9 dB 7.5 dB .001]

Voice: [5.5 dB 4 dB .001]

Fixed rate video: [7 dB 5.5 dB .001]

Figure 7.10: Unsymmetrical multimedia traffic (Fixed rate video + voice) with imperfect power control (2 dB error)

Ratio of number of voice to video connection: 3:1

Q-vectors:

Fixed rate video: [13.5 dB 12 dB .001]

Voice: [5.5 dB 4 dB .001]

Figure 7.11: Unsymmetrical multimedia traffic (Fixed rate + variable rate video) with imperfect power control (2 dB error)

Ratio of number of fixed rate video to variable rate video connection: 5:1

Q-vector:

Variable rate video: [13.5 dB 12 dB .001]

Fixed rate video: [9 dB 7.5 dB .001]

7.9 Adaptive equivalent bandwidth (Simulation study)

The proposed technique for adaptive call admission control has been tested by extensive simulation experiments. The kernel estimator is employed for estimating the L^{th} percentile of interference power distribution.

A single radio cell with infinite population is considered, and the call arrival process is assumed to be a Poisson process. Holding times are assumed to be exponentially distributed with a mean of 150 s for all three classes of traffic. The total arrival rate is divided evenly among different media. 2 dB error in power control mechanism is considered.

The minimum acceptable signal to interference ratio for voice traffic is considered to be 4 dB; for fixed rate video it is set at 5.5 dB; and 7.5dB is the minimum acceptable signal to interference ratio for variable rate video. Required average S/I is assumed to be 1.5 dB higher than the required minimum S/I.

We studied the convergence and tracking performance of the adaptive equivalent bandwidth technique. The simulation program was run for three different adaptation factors. Heavy traffic intensity is considered (90 Erlang), which is the worst case scenario for access control due to the large number of arrivals between two successive interference measurements. Samples are collected over a five-second window with a sampling resolution of .5 ms. The results are presented in Figure 7.12. In these curves, the error (Y-axis) represents the relative difference between the estimated L^{th} percentile derived from adaptive equivalent bandwidth algorithm and the measured L^{th} percentile using kernel estimator. The distribution of the total interference power and the actual outage probability are shown in Figure 7.13. Interestingly, there is an optimum value for the adaptation rate that balances fast convergence with good tracking; this value was found to be around .05.

Blocking and outage probability under different traffic intensities are derived through simulation and were compared with a regular equivalent bandwidth technique. The results are shown in Figures 7.14 and 7.15. The adaptation factor was set at .05 during this simulation. Average required S/I is set 1.5 dB higher than the minimum required S/I for all three classes of traffic. The effect of the outage threshold, as well as minimum required signal to interference ratios on the blocking probability, is studied. Simulation results are presented in Figures 7.16 and Figures 7.17.

The simulation results show that the proposed adaptive access technique has improved the regular equivalent bandwidth utilization considerably. The price was added complexity, primarily due to the interference measurement. This observation may not represent a significant complexity because tracking the interference level is required for the purpose of closed-loop power control. From Figures 7.16 and 7.17, one can conclude that there is a trade-off between blocking probability and outage threshold. The larger the threshold, the smaller the blocking probability is. Apparently, the blocking probability is more sensitive to the minimum level of required S/I thresholds than the outage thresholds.

Figure 7.12: Convergence speed and tracking performance for different adaptation coefficients

Figure 7.13: Interference power distribution for different adaptation coefficients

(Interference power level is normalized by the background noise power)

Figure 7.14: Blocking probability for regular and adaptive equivalent bandwidth technique (2 dB error in power control)

Figure 7.15: Overload probability versus traffic intensity for adaptive equivalent bandwidth technique

Figure 7.16: Average blocking probability versus outage threshold

Figure 7.17: Average blocking probability versus minimum required S/I threshold

7.10 Relationship between adaptive equivalent bandwidth indices and traffic parameters (Analysis)

In this section, a closed form expression for the adaptive equivalent bandwidth vector is derived that describes the relationship between the adaptive equivalent bandwidth indices and the traffic parameters. Some approximations are used to carry out the derivation. Underlying assumptions are then outlined.

The scope of this analysis is limited to a single cell CDMA with zero inter-cell interference. Due to the inter-dependency of power levels in a multimedia CDMA network, a general analysis becomes intractable very quickly.

CDMA cell capacity is a function of the number of mobiles in the cell through the cell capacity's dependency on the power coefficient $\Upsilon_{opt}(N)$. This can be seen from the tele-traffic model of a multimedia CDMA base station in Chapter 6. Estimating the equivalent bandwidth vector becomes very complicated if the dependency of the cell capacity on the number of mobiles in the cell is included in the analysis. In order to carry out the analysis, it is assumed that the total received power at the base station is much larger than the background noise power. Under this assumption, cell capacity can be considered independent from the number of mobiles in the cell.

If the background noise power is negligible, the outage constraint for the i^{th} mobile in the cell in a single cell CDMA scenario, assuming that linear power assignment is implemented as the underlying power assignment method, can be written as

$$Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)_i^*\right) = Prob\left(\frac{\Upsilon_{opt}(N) \cdot \left(\frac{S}{I}\right)_i^+ \cdot 10^{(\xi_i)/10} \cdot U_i}{\frac{R}{W} \left[\sum_{j=1}^N \Upsilon_{opt}(N) \cdot \left(\frac{S}{I}\right)_j^+ \cdot 10^{(\xi_j)/10} \cdot U_j \right]} \leq \left(\frac{S}{I}\right)_i^*\right) \quad \text{Eq(7.22)}$$

Eq(7.22) can be further simplified as

$$Prob\left(\left(\frac{S}{I}\right)_i \leq \left(\frac{S}{I}\right)_i^*\right) = P_{max,i} \cdot Prob\left(\left(\sum_{j=1}^N \left(\frac{S}{I}\right)_j^+ \cdot 10^{(2\xi_j)/10} \cdot R \cdot U_j\right) \geq \frac{W}{\beta_i}\right) \quad \text{Eq(7.23)}$$

Because outage constraints don't depend on $\Upsilon_{opt}(N)$, this observation implies that the cell capacity for the outage server in the tele-traffic model is fixed and is equal to W/β_i .

The Gaussian approximation for the PDF of the interference power is another assumption in our analysis. For a given number of users, the probability density function of the total power received at the cell site can be approximated by a Gaussian random variable. This approximation is not true if the received power levels from the mobiles have a wide spread. However, the Gaussian approximation allows a closed form expression for $MRC(L)$ to be derived as

$$MRC(L) = \sqrt{2} \cdot Q^{-1}(L) \left[\left(\sum_{i=1}^{Nc} n_i \cdot \Lambda_i^2 \right)^{1/2} \right] + \sum_{i=1}^{Nc} n_i \cdot m_i \quad \text{Eq(7.24)}$$

where Nc is the total number of traffic classes. n_i is the number of users from each class of traffic. m_i is the average received power at the base station for class i traffic and is calculated as

$$m_i = \left(\frac{S}{I} \right)^+ \cdot 10^{\overline{\xi}/10} \cdot U_i \quad \text{Eq(7.25)}$$

Λ_i^2 is the variance of the received power from a class i user and can be calculated as

$$\Lambda_i^2 = \left[P_{i1} e^{(2 \times (\beta \Delta)^2)} - (P_{i1})^2 (e^{((\beta \Delta)^2/2)})^2 \right] \left(\frac{S}{I} \right)^{+2} \quad \text{Eq(7.26)}$$

$P_{i1} = \text{prob}(U_i = 1)$, Δ^2 is the variance of ξ and $Q^{-1}(\cdot)$ is the inverse $Q(\cdot)$ function where

$$Q(x) = \frac{1}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$

The Minimum Mean Square Error (MMSE) problem described by Eq(7.14) can be formulated in terms of user traffic parameters by using the expression for $MRC(L)$ derived in Eq(7.24).

find $\{e_1, e_2, \dots, e_{Nc}\}$ that minimizes

$$\sum_{n_1=0}^{Max_1} \dots \sum_{n_{Nc}=0}^{Max_{Nc}} \left\{ \sqrt{2} Q^{-1}(L) \left(\sum_{i=1}^{Nc} n_i \cdot \Lambda_i^2 \right)^{1/2} + \sum_{i=1}^{Nc} n_i \cdot m_i - \sum_{i=1}^{Nc} n_i \cdot e_i \right\}^2 f(n_1, \dots, n_{Nc})$$

where $f(n_1, \dots, n_{Nc})$ is the joint probability distribution function of the number of users from each class of traffic; Max_i is the maximum number of admissible users from class i and is calculated as

$$Max_i = \frac{(W/\beta)}{e_i}$$

Based on the theory of reversible stochastic networks, it can be shown that the joint probability distribution function of the number of users in the cell is separable and insensitive to the distribution of the call holding time [44][46][67]. This theory is applicable in the single cell CDMA scenario due to the fact the poisson arrival is assumed and mobiles capacity demand are independent from each others. Therefore, the joint probability distribution function of the active number of mobiles in the cell assumes the product form and can be calculated as follows:

$$f(n_1, \dots, n_{Nc}) = \begin{cases} (1/G) \prod_{i=1}^{Nc} \frac{(\lambda_i/\mu)^{n_i}}{(n_i)!} e^{-\frac{\lambda_i}{\mu}} & \text{if } (n_1, \dots, n_{Nc}) \in S \\ 0 & \text{if } (n_1, \dots, n_{Nc}) \notin S \end{cases}$$

$$G = \sum_S \frac{(\lambda_i/\mu)^{n_i}}{(n_i)!} e^{-\frac{\lambda_i}{\mu}} \quad \text{Eq(7.27)}$$

$$S: \{n_1, \dots, n_{Nc}\} \text{ where } \left(\sum_{i=1}^{Nc} n_i \cdot e_i \leq (W/\beta) \right)$$

where λ_i is the inter-arrival time for class i traffic, and μ is the holding time for the same class of users.

Values of adaptive equivalent bandwidth indices can be found using the following equation:

$$\nabla_e \cdot \Phi = 0. \quad \text{Eq(7.28)}$$

where

$$\Phi = \sum_{n_1=0}^{Max_1} \dots \sum_{n_M=0}^{Max_{Nc}} \left\{ \sqrt{2} Q^{-1}(L) \left(\sum_{i=1}^{Nc} n_i \cdot \Lambda_i^2 \right)^{1/2} + \sum_{i=1}^{Nc} n_i \cdot m_i - \sum_{i=1}^{Nc} n_i \cdot e_i \right\}^2 f(\mathbf{n})$$

and ∇_e is the Gradient operator with respect to the equivalent bandwidth vector e .

Because both the scaling factor G and the limits on the maximum number of users in the cell (Max_i) are functions of adaptive equivalent bandwidth indices themselves, a closed form solution for the minimization problem could not be found. Using the Gaussian approximation helps to solve this problem. The value of the maximum number of users from the i^{th} class of traffic can be found from the following equation:

$$\begin{aligned} \sqrt{2} \cdot Q^{-1}(L) (Max_i \cdot \Lambda_i^2)^{1/2} + Max_i \cdot m_i &= (W/\beta) \\ Max_i &= \left[\frac{-\sqrt{2} Q^{-1}(L) \cdot \Lambda_i + \sqrt{(Q^{-1}(L))^2 \cdot 2\Lambda_i^2 + 4m_i \cdot \frac{W}{\beta}}}{2 \cdot m_i} \right]^2 \end{aligned} \quad \text{Eq(7.29)}$$

and scaling factor of G can be written as

$$\begin{aligned} G &= \sum_S \frac{(\lambda_i/\mu)^{n_i}}{(n_i)!} e^{-\frac{\lambda_i}{\mu}} \\ S &: \{n_1, \dots, n_{Nc}\} \text{ where} \\ \sqrt{2} \cdot Q^{-1}(L) \left[\left(\sum_{i=1}^{Nc} n_i \cdot \Lambda_i^2 \right)^{1/2} \right] + \sum_{i=1}^{Nc} n_i \cdot m_i &\leq \left(\frac{W}{\beta} \right) \end{aligned} \quad \text{Eq(7.30)}$$

As a direct consequence of the gradient operation, equation (7.28) can be written in matrix form as $A \cdot e = B$ where e is the adaptive equivalent bandwidth vector $e = [e_1 \ e_2 \ e_3]$. Therefore, vector e can be found from the following matrix equation:

$$e = A^{-1} \cdot B \quad \text{Eq(7.31)}$$

For a cell with three classes of traffic, matrix A and B are found as

$$A = \begin{bmatrix} \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_1^2 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_1 n_2 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_1 n_3 f(n) \\ \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_1 n_2 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_2^2 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_2 n_3 f(n) \\ \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_1 n_3 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_2 n_3 f(n) & \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} n_3^2 f(n) \end{bmatrix}$$

$$B = \begin{bmatrix} \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} \left(\sqrt{2} Q^{-1}(L) \left(\sum_{i=1}^3 n_i \cdot \sigma_i^2 \right)^{1/2} + \sum_{i=1}^3 n_i \cdot m_i \right) n_1 f(n) \\ \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} \left(\sqrt{2} Q^{-1}(L) \left(\sum_{i=1}^3 n_i \cdot \sigma_i^2 \right)^{1/2} + \sum_{i=1}^3 n_i \cdot m_i \right) n_2 f(n) \\ \sum_{n_1=0}^{Max_1} \sum_{n_2=0}^{Max_2} \sum_{n_3=0}^{Max_3} \left(\sqrt{2} Q^{-1}(L) \left(\sum_{i=1}^3 n_i \cdot \sigma_i^2 \right)^{1/2} + \sum_{i=1}^3 n_i \cdot m_i \right) n_3 f(n) \end{bmatrix}$$

One can find the optimum values of adaptive equivalent bandwidth indices from this set of matrixes and equation (7.31). Blocking probability and other system performance measures can be estimated using the calculated equivalent bandwidth vector.

To validate the analytical results, a set of simulation is conducted. The first set of simulations was implemented based on a single cell CDMA with two classes of ON-OFF Markovian sources. The adaptive equivalent bandwidth indices for different traffic intensities are estimated through simulation and are compared with the values of adaptive equivalent bandwidth indices that are derived from equation (7.31). The results of this experiment are shown in Figures 7.18 and 7.19. These curves are derived for different minimum required S/I. The second experiment extended the results of the first experiment to a multimedia case with three classes of traffic. The result is shown in Figure 7.20. Imperfect power control with 2dB error is considered.

From these sets of curves, one can conclude that analytical results provide a reasonable prediction of the actual values of adaptive equivalent bandwidth indices. The accuracy of analysis degrades for lower traffic intensity, this observation can be explained by the fact that at low intensity traffic, the average number of users present in the cell is smaller than

the case of high intensity traffic and consequently the Gaussian approximation for the interference power is less accurate.

Figure 7.18: Comparison between theoretical and simulation results

Two ON-OFF Markovian sources:

Traffic parameters (class 1): 40 % activity ratio with 5 dB minimum required S/I
(class2): 60 % activity ratio with 7 dB minimum required S/I

Figure 7.19: Comparison between theoretical and simulation results

Two ON-OFF Markovian sources:

Traffic parameters (class 1): 40 % activity ratio with 7 dB minimum required S/I
(class2): 60 % activity ratio with 9 dB minimum required S/I

Figure 7.20: Comparison between theoretical and simulation results

Multimedia traffic:

Traffic parameters

(Variable rate video): minimum required S/I is equal to 7 dB

(Fixed rate video): minimum required S/I is equal to 5.5 dB

(Voice): minimum required S/I is equal to 4 dB

7.11 Blocking probability for multimedia CDMA (Analysis)

Equivalent bandwidth indices which were calculated in the last section can be thought of as the amount of capacity that each type of traffic requires. A connection request is blocked if the remaining capacity in the cell is less than the equivalent bandwidth index of the requesting user.

Due to the functional similarity of the above model with a circuit switch network, the blocking probability in a CDMA cell can be calculated using the methods developed for calculating the blocking probability in a circuit switching network [44][45][46].

In this section, blocking probability is calculated for a single cell CDMA where the effect of inter-cell interference is ignored.

A general expression for blocking probability based on the reversible stochastic network principle [45] can be derived as (for a type "i" traffic)

$$Pb_i = 1 - \frac{G(C - e_i, Nc)}{G(C, Nc)} \quad \text{Eq(7.32)}$$

where Pb_i is the blocking probability for the i^{th} class of traffic; $G(C, Nc)$ is the scaling factor which was introduced in the previous section and is repeated here for reference:

$$G(C, Nc) = \sum_S \frac{(\lambda_i/\mu)^{n_i}}{(n_i)!} e^{-\frac{\lambda_i}{\mu}} \quad \text{Eq(7.33)}$$

$$S: \{n_1, \dots, n_{Nc}\} \text{ where } \sum_{i=1}^{Nc} n_i \cdot e_i \leq C$$

$$\text{and } C = \frac{W}{\beta}$$

e_i is the adaptive equivalent bandwidth index and Nc is the total number of traffic classes. Because the cardinality of S grows roughly as C^{Nc} [44], the brute force computation of the Eq(7.33) is ruled out. A one dimensional recursion developed by Kauffman [44] is used in this work to calculate the $G(\cdot)$, and the blocking probability is found accordingly.

$G(C, Nc)$ is computed recursively as follows:

$$\begin{aligned}
 G(j, i) &= \sum_{l=1}^{\lfloor j/e_i \rfloor} \frac{(\lambda_i/\mu)^l}{(l)!} e^{-\frac{\lambda_i}{\mu}} G(j-l \cdot e_i, i-1) & i = 2, \dots, Nc \\
 & & j = 0, 1, \dots, C
 \end{aligned} \tag{Eq(7.34)}$$

$$\text{and } G(j, 1) = \sum_{l=0}^{\lfloor j/e_1 \rfloor} \frac{(\lambda_1/\mu)^l}{(l)!} e^{-\frac{\lambda_1}{\mu}}$$

Consistency between analysis and simulation is tested, and the results are reported in Figure 7.21. A single cell CDMA with 2dB error in power control is considered.

We found that predicted values of blocking probability are reasonably close to the values derived from the simulation in medium and high traffic intensity. Analysis is less accurate in low traffic intensity. This problem can be traced back to the accuracy of the underlying Gaussian approximation for interference power. The Gaussian approximation is less accurate when the number of mobiles in the cell is small—similar to the case of low intensity traffic.

Figure 7.21: Comparison between the analytical estimate and simulation results for blocking probability

7.12 Two level access control strategy

Most of the published research work on access control for CDMA focussed either on call admission control only [10][17][21][25][109] or on packet level control [9]. In this thesis, a two level control strategy is proposed that efficiently integrates packet and call level controls.

At the packet level, the relative delays among packets transmitted by the users are regulated. Delays are scheduled in a way that minimizes the variance of intra-cell interference. Delay schedule is enforced by the base station through forwarding control packets on down link to the admitted mobiles. The role of control packets is similar to that of control packets in a polling scheme.

At the call level, admission control based on adaptive equivalent bandwidth technique is employed. Because equivalent bandwidth indices are modified adaptively, based on the periodical measurement of interference power, the minimized interference due to the packet level control will lead to smaller adaptive equivalent bandwidth indices at the call level; and consequently, smaller blocking probability and better bandwidth utilization is expected. The linear power assignment algorithm is assumed to be implemented as the underlying power assignment method.

7.12.1 Multi-layer access control technique

This section consists of two subsections. In the first subsection, the proposed packet level control algorithm is outlined. In the second subsection, the combined call and packet level control algorithm is explained.

7.12.2 Delay scheduling

As it was mentioned in Chapter 4, users are transmitting independently every 10ms in a periodical fashion. Therefore user k that is admitted in the cell at time t_k will initiate the transmission at time instants:

$$\{t_k, (t_k + 10), (t_k + 20), \dots\}$$

The intuition behind our proposed delay scheduling technique is to distribute the interference energy as evenly as possible during a 10ms time slot. Uniform distribution of interference energy with respect to the delay will result in the minimization of the variance

of interference which leads to a lower overload probability. We explain this concept in more details in what follows.

Assuming a slotted time axis (10 ms slot) and denoted by D_K , the start time for transmission by user k in a 10 ms time slot (D_K is called the delay parameter for user k in this chapter). The intra-cell interference at time t , denoted by $I(t)$, can be written in general as

$$I(t) = \sum_{k=1}^N V_k(t) \cdot 10^{\zeta_k/10} \cdot \left(\frac{S}{I}\right)_k^+ \cdot \Upsilon_{opt}(N) \quad \text{Eq(7.35)}$$

$V_k(t)$ is a random variable that assumes two values: one and zero according to the following probability distribution function.

$$\begin{aligned} \text{prob}(V_k(t) = 1) &= \pi_K^1(t) \\ \text{prob}(V_k(t) = 0) &= 1 - \pi_K^1(t) \end{aligned} \quad \text{Eq(7.36)}$$

where

$$\pi_K^1(t) = \text{prob}(D_k \leq [t]_{10} \leq D_k \oplus P_K^1(t) \cdot 10\text{ms})$$

" $\oplus$ " is the modulo 10 addition and $[t]_{10}$ is the time index in modulo 10 format; $P_K^1(t)$ is an attribute of the user's activity ratio and is explained shortly.

The probability distribution of $U_k(t)$ (the activity ratio of user k at time t) can be written as

$$\begin{aligned} \text{prob}(U_k(t) = 1) &= P_K^1(t) \\ \text{prob}(U_k(t) = 0) &= P_K^0(t) \end{aligned}$$

Because the variable rate traffic is included in the mixture of traffic, the probability distribution function of the activity ratio will be time variable.

The variance of interference at time t for a given set of $\{D_i\}$ $i = 1 \dots N$, after some mathematical manipulation, can be calculated as

$$R(t) = \sum_{k=1}^N \left(\left(\frac{S}{I} \right)_k^+ \right)^2 \cdot R_k(t) \cdot \Upsilon_{opt}^2$$

$$R_k(t) = \left[\pi_k^1(t) e^{(2 \times (\varepsilon \Delta)^2)} - (\pi_k^1(t))^2 (e^{((\varepsilon \Delta)^2/2)})^2 \right] \quad \text{Eq(7.37)}$$

$\varepsilon = \frac{\ln(10)}{10}$ and Δ is the variance of user power level due to imperfect power control. Interference power, in general, is not a stationary process. In this section, we use the term variance of interference without time index where we refer to the mean value of variance.

Finding the exact values for $\{D_i\}$ that minimizes the variance of interference requires the use of an exhaustive numerical search method. However, by using an approximation for $R(t)$ (presented shortly) a general rule for assigning delays to the users can be found:

Assuming $\pi_k^1(t) \ll 1$ then $R(t)$ can be approximated as

$$R(t) = \sum_{k=1}^N \left(\left(\frac{S}{I} \right)_k^+ \right)^2 \cdot \left[\left(\pi_k^1(t) e^{(2 \times (\varepsilon \Delta)^2)} \right) \Upsilon_{opt}^2 \right] \quad \text{Eq(7.38)}$$

By grouping the users according to the value of $\left(\frac{S}{I} \right)_k^+$ into three groups (assuming three types of media are present) and rewriting the expression for $R(t)$ we can get

$$R(t) = e^{(2 \times (\varepsilon \sigma)^2)} \sum_{m=1}^3 \sum_{j=1}^{N_m} \left(\left(\frac{S}{I} \right)_m^+ \right)^2 (\pi_{i,m}^1(t)) \quad \text{Eq(7.39)}$$

where N_m is the total number of users that belong to the type m media and

$$N = \sum_{m=1}^3 N_m$$

A guideline for assigning the delay parameters to the users could be stated as

Delays should be assigned in a way that users with high energy per bit or high $\left(\frac{S}{I} \right)_k^+$ should have smaller Π_m^1 where

$$\Pi_m^1 = \sum_{j=1}^{N_m} (\pi_{i,m}^1(t)) \quad \text{Eq(7.40)}$$

In this thesis, we propose two suboptimal scheduling algorithms by following the above mentioned rule.

7.12.3 Fixed delay scheduling

In this scheme, the delay schedule is updated every time a user arrives or departs to/from the cell. Delay parameters $\{D_i\}$ will be assigned to the users in a way that minimizes the overlapping among the users in the delay dimension and, at the same time, tries to maximize the distance among the users with higher energy per bit. The procedure for assigning the $\{D_i\}$ is then introduced.

The scheduler sorts the users in descending order according to their energy per bit and calculates the delay parameter for each user based on the following simple loop:

$$\begin{aligned}
 D_1 &= 0 \\
 \text{for } k &= 2:N \\
 D_k &= D_{k-1} \oplus (U_{k-1} \times 10) \\
 \text{end}
 \end{aligned}
 \tag{7.41}$$

In this algorithm, $U_k(t)$ is approximated by its average value U_k , and users are separated by their active interval period approximated by $U_{k-1} \times 10ms$.

A graphical representation of this algorithm is shown in Figure 7.22. To keep the figure simple, perfect power control is assumed.

Figure 7.22: Graphical representation of delay scheduling

7.12.4 Adaptive delay scheduling

To take into account the effect of variable rate traffic more accurately, instead of using the pre-calculated average activity ratio, we propose to estimate it periodically (every T seconds) through monitoring users' activity ratios and updating the delay schedule every T seconds.

The fixed scheduling algorithm is modified (at its m^{th} update), as follows, to take into account the time variation in activity ratio random variable.

$$\begin{aligned}
 &D_1 = 0 \\
 &\text{for } k = 2:N \\
 &D_k = D_{k-1} \oplus (\Pi_{k-1}(mT) \times 10ms) \\
 &\text{end}
 \end{aligned}
 \tag{Eq(7.42)}$$

7.12.5 Call admission control

Admission control is based on adaptive equivalent bandwidth. When the proposed delay scheduling algorithm is linked with the call admission scheme, the empirical probability distribution $f_{\bar{n}}(t)$, which is estimated at the base station, will have a lower variance compared to the scenario without scheduling. An smaller value of $MRC(L)$ is expected to be achieved from the $f_{\bar{n}}(t)$ with a smaller variance.

From Eq(7.14), one can conclude the smaller $MRC(L)$ will lead to an equivalent bandwidth vector with a smaller norm; and consequently a higher number of admitted users in the cell is expected.

7.13 Simulation Results

The proposed technique for admission control has been tested through detailed simulation experiments. A single radio cell with infinite population is assumed where calls arrive according to an exponential distribution. Holding times are assumed to be exponentially distributed with a mean of 150 seconds for all three types of traffic. The total arrival rate is divided evenly among the different media.

The minimum acceptable signal to interference ratio for voice traffic is considered to be 4 dB; for a fixed rate video it is set at 5.5 dB, and 7.5dB is the minimum acceptable signal to interference ratio for variable rate video. Required average S/I is set 1.5 dB higher than the required minimum S/I.

The first set of experiments is aimed at showing the effectiveness of delay scheduling in reducing the interference power variance. For a fixed number of users in the cell (no call arrival or departure), the variance of interference is measured with and without scheduling. Results are shown in Figure 7.23. Adaptive scheduling with a 1.2 second update period was used in this experiment. In Figure 7.24, we show the actual distribution of interference when there are 14 users in the cell from each class of traffic (total of 42 users). As it can be seen from Figure 7.24, the tail of interference power distribution has been reduced considerably. Blocking probability for different schemes (averaged over different types of traffic) is shown in Figure 7.25. Clearly, significant improvement is achieved by using packet scheduling—both fixed and adaptive.

The combination of proposed adaptive access control and delay scheduling proved to be an effective technique in providing guaranteed QOS for users in a CDMA cell. The complexity due to scheduling may be well justified considering the significant improvement in the bandwidth utilization.

Figure 7.23: Interference variance with and without delay scheduling

Figure 7.24: Interference distribution in a cell with 42 users
(14 users from each class of traffic)

Figure 7.25: Blocking probability as a function of traffic intensity

7.14 Adaptive access control in multiple cell CDMA network

The adaptive call admission control scheme is tested in a multiple cell CDMA network. Other cell interference might have considerable adverse effects on the access control scheme due to its unpredictable characteristics. Some new features have been added to the proposed access control technique in order to take into the consideration the effect of inter-cell interference. These added features are outlined in this section.

Because inter-cell interference can significantly affect the accuracy of call admission decisions, the main objective in this section is to study the effect of inter-cell interference on the call level admission control performance. The packet level control algorithm is not expected to be affected adversely by inter-cell interference.

7.14.1 Inter-cell interference and adaptive equivalent bandwidth technique

Inter-cell interference will reduce the cell capacity. Furthermore, due to the time variation in the level of other cell interference power, the cell capacity is time variable. Access control based on adaptive equivalent bandwidth indices can cope with the time variation in the cell capacity, as explained in the following sections.

The problem of calculating equivalent bandwidth indices in the presence of other cell interference can be formulated as finding an equivalent bandwidth vector ($e = [e_1 \ e_2 \ e_3]$) that minimizes the following error function in an average sense:

$$error = [K \cdot e - MRC(\sigma^2, L)]^2 \quad \text{Eq(7.43)}$$

where σ^2 is the inter-cell interference power; K is the active user vector; $MRC(\sigma^2, L)$ is the L^{th} percentile of the total interference power distribution for a given inter-cell interference power level.

σ^2 is not only a function of the active user vector in the cell of interest but also is a function of active user vectors in the neighboring cells. Therefore, estimating the $MRC(\sigma^2, L)$ based on the local active user vector might be inaccurate.

Assuming that the statistics of inter-cell interference changes slowly with time compared to the intra-cell interference [16], it is possible to find an optimum equivalent bandwidth vector that can accurately estimate the MRC value. Due to the slow time variation in the MRC , one can expect that the optimum equivalent bandwidth vector will be time variable as well.

Eq(7.43) can be modified based on the assumption of a slow time variable inter-cell interference process as

Find $e_{(T)}$ that minimizes the following error function:

$$error_{(T)} = [K \cdot e_{(T)} - MRC(\sigma_{(T)}^2, L)]^2 \quad \text{Eq(7.44)}$$

$e_{(T)}$ is the equivalent bandwidth vector that minimizes the average error function $error_{(T)}$ over a time window of T. It is assumed that the inter-cell interference statistics don't change over T units of time.

There are two possible methods for adjusting the equivalent bandwidth vector in the presence of inter-cell interference

- (a) Direct adaptation based on total interference power
- (b) Adaptation based on intra-cell interference only

In the first approach, a gradient descent algorithm is used to modify the equivalent bandwidth indices directly, based on the estimated MRC value of the total interference power without differentiating between inter and intra-cell interference.

The admission control process in this scenario is carried out similarly to the single cell situation. This reason is that the inter-cell interference is included in the adaptation of equivalent bandwidth indices directly. In other words, a call is admitted if

$$\sum_{i=1}^{N_c} n_i \cdot e_i \leq \frac{W \cdot \gamma_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.45)}$$

The second method, which is less general than the first method, is based on the assumption that the inter-cell interference power over the time window of T can be approximated by its average value. Using this approximation, $MRC(\sigma_{(T)}^2, L)$ can be simplified as

$$MRC(\sigma_{(T)}^2, L) = MRC(L) + \overline{\sigma_{(T)}^2} \quad \text{Eq(7.46)}$$

In general, $MRC(.)$ is not an additive operator—in other words $MRC(a+b) \neq MRC(a) + MRC(b)$ where a and b are independent random variables.

However, if b is a constant then $MRC(a + b) = MRC(a) + b$. This result can be verified directly from the definition of $MRC(.)$.

The error function can be written using the expression for MRC in Eq(7.45), as

$$error_{(T)} = \left[K \cdot e_{(T)} - \left(MRC(L) - \overline{\sigma_{(T)}^2} \right) \right]^2 \quad \text{Eq(7.47)}$$

Based on the above expression for error function, the equivalent bandwidth vector can be adjusted using the gradient descent algorithm based on the value of the L^{th} percentile of intra-cell interference power.

The admission decision criterion for the second method is calculated according to the following equation. A call is admitted if

$$\sum_{i=1}^{N_c} n_i \cdot e_i + \overline{\sigma_{(T)}^2} \leq \frac{W \cdot \gamma_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.48)}$$

A simple simulation experiment was implemented to investigate the relative performance of two methods of adapting equivalent bandwidth vector. A single cell CDMA with three classes of traffic is considered.

As traffic intensity increases in the cell, the variation in the intra-cell interference power increases, which makes it more difficult for gradient descent algorithm to track the changes. Total traffic intensity of 56 Erlang is considered as the worst case test scenario for the adaptation algorithm.

Linear optimum power assignment is implemented as the underlying power assignment method, and inter-cell interference is simulated as an independent process where the state of the process (interference power level) changes according to a uniform distribution. The value of interference level is normalized with respect to the spreading ratio (W/R).

A sample path of inter-cell interference where the relative interference level is in the range of zero and 30% is shown in Figure 7.26.

The tracking performance of adaptive equivalent bandwidth in the presence of inter-cell interference is studied for different residency time in the inter-cell interference model. Estimation error is defined by the square root of the value derived from equation(7.44) (averaged over a long period of time). Results of this experiment are presented in Figure (7.27).

As one could expect, measuring the inter-cell interference provides better tracking performance for the adaptive equivalent bandwidth algorithm than the first approach. However, the direct approach is adopted in this report because of the inherited simplicity and generality and the diminishing gain in the approach based on inter cell interference measurement.

Figure 7.26: A sample path of inter-cell interference with 10 seconds average residency time at each state

Figure 7.27: Effect of inter-cell interference on tracking performance of adaptive equivalent bandwidth algorithm

7.15 Adaptive access control with back-off strategy

In a distributed access control scheme, base stations carry out the admission process independently from each other. Distributed access control has the advantage that it doesn't put a significant burden on the backbone network for the exchange of control information. Another advantage of the distributed scheme stems from the fact that the network can be reconfigured easily. However, because the base stations operate in an uncoordinated fashion, the variation in the cell capacity due to inter-cell interference can not be controlled.

The offered load to a cell has significant impact on the performance of call admission control. In general, it is known that even if a call admission control agent makes the correct decision on any single occasion with high probability, it may not be enough when the traffic load is high and the traffic parameters are variable [28]. In other words, the rate at which calls are admitted in error may become too large. The reduction in cell capacity due to inter-cell interference (a time variant variable) means that cell traffic might enter the overload region frequently. By analogy to the ATM switch model [28], a cell is called overloaded if

$$\sum_{i=1}^{Nc} \left(\frac{\lambda_i}{\mu_i} \right) \cdot e_i \geq \frac{W \cdot \gamma_{opt}}{\beta} - \sigma_T^2 \quad \text{Eq(7.49)}$$

where Nc is the number of traffic classes, λ_i and μ_i are the arrival rate and departure rate for the i^{th} class of traffic respectively, and e_i is the adaptive equivalent bandwidth index for the i^{th} class of traffic.

A back-off defence strategy against high offered load was proposed by Bean [6] to improve the performance of admission control for ATM switches in heavy traffic condition with uncertainty in the traffic parameters. The main idea in the proposed back-off strategy is creating delay in admitting a new call following a rejection decision [6][28].

Several variations of back-off strategy are outlined in [28]. The following strategy, which has the essential features of a good scheme, is adopted in this thesis due to its simplicity.

In a multimedia CDMA cell under overload condition, if a call request is rejected, no user from that class of traffic will be admitted until a call currently in progress from a similar class is completed.

Some analytical insight into back-off strategy when it was applied as part of an admission control algorithm for single class of traffic in an ATM switch is provided in [28].

The performance of adaptive access control with back-off strategy is evaluated by simulation. Optimum linear power assignment is considered as the underlying power assignment method. Access control based on the adaptive equivalent bandwidth technique is used to admit/reject the users in the cells. The values of the maximum power ratio coefficients is considered to be available in the base stations. Transmitter power limit is set at 1.8 watt in this set of experiments.

A sixteen cell network is simulated. Users arrive in the cells according to a Poisson process. Equal arrival rates among different classes of traffic, as well as among different cells, are considered in this set of simulations, and users are distributed uniformly in the cells.

A network geographical specification is provided in Chapter 4 and is shown in Figure 4.1. Only fourth order attenuation is simulated; lognormal shadowing is not considered, and perfect power control is assumed. System performance in terms of overload probability and average blocking probability is estimated. Results are averaged over the four inner cells in the network. The target value for outage probability was set at .001.

The outcome of this simulation test are shown in Figures 7.28 and 7.29. From these sets of curves, it can be concluded that adaptive access control equipped with a back-off defence mechanism is robust enough to cope with variable cell capacity. However, the back-off strategy imposes an unnecessary higher blocking probability at a low arrival rate.

Figure 7.28: Blocking probability versus traffic intensity

Figure 7.29: Overload probability versus traffic intensity

7.16 Conclusion

In this chapter, the problem of admission control when different media with different QOS requirements are sharing a CDMA channel is studied. We proposed an adaptive access control method based on the equivalent bandwidth theory and the cell load measurement. We showed that the proposed algorithm allows efficient integration of speech and low bit rate video in an outdoor CDMA cellular network with imperfect power control.

The combination of the proposed adaptive access control and delay scheduling proved to be an effective technique in providing guaranteed QOS for users in a CDMA cell. The complexity due to the scheduling approach may well be justified considering the significant improvement in the bandwidth utilization.

The impact of the time variable inter-cell-interference on the access control mechanism is addressed in this chapter. The combined adaptive access control and back-off strategy proved to be an effective technique in dealing with the variable cell capacity problem.

Chapter 8

Conclusions and future work

The vision of untethered communication of media in any form still faces significant technical hurdles. This thesis attempts to identify some of the key challenges and to discuss possible solutions, but it is by no means complete.

Summary

The limited capacity of the wireless multiple access channel motivated the need for efficient radio resource management. In this thesis, we specialized on power management and call admission control due to their important role in a comprehensive radio resource management scheme for a multimedia CDMA network.

Chapter 3 began with the study of some fundamental aspects of a multimedia CDMA network. Fixed and variable processing gain schemes for transmission in a CDMA air interface are two viable options. There was not a clear criterion in the literature for choosing one scheme over another in a CDMA cell with bursty multimedia traffic—necessitating performance comparisons part of our work.

We used a simple analytical method to compare these two techniques in terms of cell capacity utilization. It is shown that, if bursty traffic is supported in the cell, the fixed processing gain scheme can outperform the variable processing gain alternative. As a result of this comparison and some other technical considerations, the fixed processing gain scheme is adopted as the underlying transmission scheme in this thesis. However, most of the proposed algorithms are readily extendable to the variable spreading gain scheme as well.

A novel definition for QOS in a multimedia CDMA environment is proposed. The proposed quality indicator is a representative performance index for a communication link in the presence of large statistical variation in the carried traffic.

In this thesis, we argued in favor of using power assignment as a method of providing different levels of QOS for the mobiles supporting multimedia traffic. In Chapter 5, we proposed a novel power assignment and call admission control framework that serves this purpose.

The effectiveness of the proposed non-linear power assignment in providing the required QOS by the mobiles is shown.

In a wireless multimedia scenario, flexibility and robustness are highly-desirable solutions attributes. A sub-optimum but more robust framework for power assignment and admission control is studied in Chapters 6 and 7.

Linear power assignment and adaptive access control algorithms are addressed and analyzed in Chapters 6 and 7. The main outcome of our study can be outlined as follows.

The effectiveness of the adaptive equivalent bandwidth technique and the more comprehensive two-level access strategy in regulating the access to a CDMA cell is proved. Imperfect power control and inter-cell interference are considered.

An optimum linear power assignment scheme is developed. The important feature of the proposed scheme is taking into consideration the statistical variation in users' power level as well as their bit rate.

The effect of inter-cell interference on access control in a multiple cell CDMA is studied. A back-off strategy proved to be a robust technique in dealing with variation in the cell capacity.

A system performance analysis is carried out. Analysis compensates for the shortcomings of the simulation in covering all the possible combination of system parameters that affect the performance of a CDMA network. Analytical expressions for adaptive equivalent bandwidth indices are derived. The blocking probability for each class of traffic in a single cell CDMA is calculated as well.

There are many issues in the context of this thesis that require further investigation.

Because user traffic is received at different power levels at the receiver, employing a multi-user interference cancellation technique can increase the capacity.

Using interference cancellation methods changes the relationship between the interference value and the number of users in the cell from the one considered in this thesis. Applicability of adaptive equivalent bandwidth techniques for access control when interference cancellation is used in the receiver is a subject that requires further investigation.

In this thesis, only optimum cell assignment was considered. The effect of a more realistic non-optimum cell assignment on the access control mechanism is another subject for future research.

Homogeneous arrival of traffic among the cells are considered. Under heterogeneous traffic arrival, the optimum power assignment coefficients can be used to adjust the cell boundary dynamically. This concept has been referred to as cell breathing in [37][38]. Quantifying the effect of the cell breathing technique on increasing network capacity is an issue for further research.

User mobility can have a significant impact on CDMA cell capacity. Design of an access control scheme that takes into account user mobility is another interesting area for future research.

Appendix A

In this appendix, the proof of the lemmas in Chapter 5 are presented.

Lemma 1:

We show that if all the mobiles in a cell raise their transmit power by a ratio of Γ , then the ratio of increase in the inter-cell interference power level in the cell of interest (reaction to the power increase in the cell of interest by the neighboring cells) has an upper bound of Γ .

It can be shown that if all the mobiles in the rest of the network raise the level of their transmit energy per bit by a similar ratio of Γ , then the resulting power vector is a solution for the power assignment algorithm. The proof that the scaled up power vector at each cell is still a solution for the power assignment problem can be deduced from the scaling property of the effective interference function.

Because the non-linear power assignment converges to the minimum power solution, therefore the scaled up solution must be an upper bound for the actual power levels; and, consequently, the scaled inter-cell interference should be an upper bound for the actual inter-cell interference in the cell of arrival. This concludes the proof.

Lemma 2:

We show that, if all the mobiles in the network after the arrival of the new mobile raise their power by a constant ratio, derived from Eq(5.27), then the resulting power vector is a solution for the non-linear power control problem. Because the non-linear power assignment algorithm converges to the minimum power vector, therefore the calculated scaled power vector will be an upper bound for the actual power vector in the network. The details of this argument and underlying assumptions are outlined as follows.

Assume all the mobiles in the network raise their power by a ratio equal to α_j after the arrival of the new mobile in the j^{th} cell (α_j is derived from Eq(5.27). Then in the i^{th} cell ($1 \leq i \leq M$ and $i \neq j$) the value of instantaneous inter-cell interference can be calculated as

$$\sigma_i^2(N+1) \approx \left[\alpha_j + \frac{(\alpha_j \cdot (E_b^*)^* \cdot R \cdot U^*) \cdot \widehat{h^*}}{\sigma_i^2(N)} \right] (\sigma_i^2(N)) \quad (A.3)$$

where

$$\sigma_i^2(N) = \sum_{m=1}^{N_j} E_{bmj}^* \cdot R \cdot \widehat{h}_{mj}^{(i)} \cdot U_{mj} + \tilde{\sigma}^2(N)$$

$\sigma_i^2(N)$ is the inter-cell interference at the i^{th} cell before the arrival of a new mobile in the j^{th} cell.

$\tilde{\sigma}^2(N)$ is the inter-cell interference in the i^{th} cell caused by the cells other than the j^{th} cell. The contribution of the mobiles in the j^{th} cell before the new mobile arrival to the inter-cell interference in the i^{th} cell can be calculated as

$$\sum_{m=1}^{N_j} E_{bmj}^* \cdot R \cdot \widehat{h}_{mj}^{(i)} \cdot U_{mj} \quad (\text{A.4})$$

E_{bmj}^* is the m^{th} mobile received energy per bit and $\widehat{h}_{mj}^{(i)}$ is the ratio of path loss from the m^{th} mobile in the j^{th} cell to its home base station to the path loss from the same mobile to the base station in the i^{th} cell. $\widehat{h}^*$ is the path loss ratio for the new mobile. $(E_b^*)^*$ is the received energy per bit for the traffic class of the new mobile in the j^{th} cell, and U^* is the activity ratio of the new mobile.

Because the optimum cell assignment is assumed in the network, therefore

$$\widehat{h}_{mj}^{(i)} < 1 \text{ and } \text{prob} \left(\frac{(\alpha_j \cdot (E_b^*)^* \cdot R \cdot U^*) \cdot \widehat{h}^*}{\sum_{m=1}^{N_j} E_{bmj}^* \cdot R \cdot \widehat{h}_{mj}^{(i)} \cdot U_{mj} + \tilde{\sigma}^2(N)} \ll 1 \right) \approx 1 \quad (\text{A.5})$$

Based on the above assumption, the inter-cell interference value in the i^{th} cell after the arrival of a new mobile in the j^{th} cell can be approximated as follows:

$$\widehat{\sigma}_i^2(N+1) \approx \alpha_j \left(\widehat{\sigma}_i^2(N) \right). \quad (\text{A.6})$$

Using this approximation and due to the scaling property of the effective interference function, it can be concluded that if the energy per bits in the i^{th} cell ($i = 1, 2, \dots, M$, $i \neq j$) are increased by a ratio equal to α_j , then the scaled power vector is a solution for the non-linear power control problem.

We will show in the second part of the proof that the value of α_j , derived from Eq(5.27), is an upper bound for the actual power increase in the j^{th} cell. Therefore the inter-cell interference approximation derived from Eq. A.4 is an upper bound for the inter-cell interference level in the i^{th} cell. Therefore the condition of $(\alpha_j \leq \alpha_{max,i} \quad i = 1, 2, \dots, M, \quad i \neq j)$ will ensure that the power limits in the neighboring cells are satisfied.

It is important to note that due to the approximation used in Eq. A.3, theoretically, there is a non-zero probability that in some rare occasions the actual power vector might increase by a ratio larger than α_j .

In the second part of the proof, we derive a set of conditions that α_j should satisfy to ensure that the scaled power vector in the j^{th} cell is a solution for the power assignment problem. This will complete our proof since we already showed that the scaled power vector in the neighboring cells satisfy the required constraints in their corresponding cells.

By substituting the following variables in the average and outage constraints in the j^{th} cell, a set of conditions that α_j should satisfy can be found.

$E_b^*(N + \vec{1}_i)$ is replaced by $\alpha_j \cdot E_b^*(N)$ and the value of inter-cell interference is substituted by the corresponding upper bound from expression in Eq. A.4.

Average constraints:

$$\frac{\alpha_j \cdot E_{bi,j}^*}{\frac{1}{W} [\alpha_j \cdot \sigma_j^2(N) + \alpha_j \cdot (Y_{ij}) + \sigma_T^2]} \leq \left(\frac{S}{I} \right)_{ij}^+ \quad i = 1, 2, \dots, NC$$

where

$$Y_{ij} = \sum_{\substack{k=1 \\ k \neq i}}^{NC} n_k \cdot E_{bk,j}^* \cdot \bar{r}_{kj} + (n_i - 1) \cdot E_{bi,j}^* \cdot \bar{r}_{ij}$$

Outage constraints:

$$Prob \left(\frac{\alpha_j \cdot E_{bi,j}^* \cdot U_i}{\frac{1}{W} [\alpha_j \cdot \sigma_j^2(N) + \alpha \cdot X_{ij} + \sigma_T^2]} \leq \left(\frac{S}{I} \right)_{ij}^* \right) \leq L_{ij}$$

where

$$X_{ij} = \sum_{\substack{k=1 \\ k \neq i}}^{NC} n_k E_{b_{k,j}}^* \cdot R \cdot U_k + (n_i - 1) E_{b_{i,j}}^* \cdot R \cdot U_i$$

Using the Gaussian approximation for the interference power, the final form of equations in Eq(5.27) can be derived.

The conditions in Eq(5.27) guarantee that all the power and service requirements in the cell of arrival are satisfied. Furthermore, since $\alpha_j \cdot E_b^*(N)$ is an upper bound for the actual power vector, the condition of $\alpha_j \leq \alpha_{max,j}$ $j = 1, 2, \dots, M$ will guarantee that the power limits in the cell of arrival, as well as neighboring cells, will be satisfied after the admission of a new mobile.

Appendix (B)

Interference modeling in a Direct-Sequence spread spectrum cell

This appendix is based on the work reported in [92].

In this appendix, it is shown that, for a given number of users active in the cell, the variance of interference is a random variable, and the distribution of variance is a function of the user power levels. When the differences among the user power levels are large, then the distribution of the variance of interference has a large variance itself. This appendix describes the effect of user power levels on the interference variance distribution.

Assume a cell with M users that are communicating with a base station using DS-CDMA modulation. Denoted by $x_i(t)$, the i^{th} signal (received from the i^{th} user in the cell). $x_i(t)$ can be written as

$$x_i(t) = \sqrt{2P_i} \cdot \sum_{k=-\infty}^{\infty} a_{\lfloor k/N \rfloor} C_k \cdot h(t - (k + \Delta_i)T) \cos(\omega_0 t + \theta_i) \quad (B.7)$$

where $h(\cdot)$ is a rectangular chip pulse of duration T and an amplitude of one; θ_i and Δ_i are the carrier and chip phases of the i^{th} signal with respect to the desired signal. The desired signal is assigned the index of zero. The data sequence and the spreading code sequence both take the values of $\{-1, 1\}$ with equal probability. The carrier phase is assumed to be uniformly distributed in $[-\pi, \pi]$, and the chip phase is assumed to be uniformly distributed in $[0, 1]$.

Therefore the total received signal has the following general form:

$$r(t) = \sum_{i=0}^k x_i(t) + n(t) \quad (B.8)$$

At the receiver, the received signal $r(t)$ is multiplied by the replica of the spreading code of unit amplitude, followed by a multiplication by the carrier and integrating over a data symbol. Based on these assumptions for the receiver operations, the signal at the output of the receiver can be written as

$$U = \eta + \sum_{i=1}^k \sqrt{2P_i} \cdot R_{i,0}(\Delta_i) \cos(\theta_i) + N \quad (\text{B.9})$$

where N is a Gaussian distributed random variable with zero mean and variance $V_0 = NTN_0/2$, and $R_{i,0}(\Delta_i)$ is the correlation function between the spreading code of the interfering signal and the desired signal. η is equal to

$$\eta = \sqrt{2P_0}NT \quad (\text{B.10})$$

Assuming a hard decision detection scheme, the probability of symbol error will be

$$p = P[Z > \eta] \quad (\text{B.11})$$

The distribution function of Z is derived under two scenarios:

- (a) single interferer
- (b) multiple interferers

In the case of a single interferer, the random variable Z (interference) can be expressed as

$$Z = T\sqrt{2P_1}(\Delta_1\beta_1 + (1 - \Delta_1)\beta_2)\cos(\theta_1) \quad (\text{B.3})$$

where β_1 and β_2 are i.i.d random variables with a binomial distribution function $b(\cdot)$. This expression for Z can be understood with the help of equation (B.1), which represents the correlation of two spreading codes with a chip offset of Δ_1

Fig(B.1)

As can be seen from equation (B.1), Z_i is the sum of $2N$ random variables $f_i = e_i \cdot d_i$ where $i = 1, 2, \dots, 2N$ and d_i take values from the set $\{-1, +1\}$, and the sequence $\{e_i\}$ alternates between Δ_1 and $1 - \Delta_1$. As the processing gain becomes larger, the binomial distribution approaches a Gaussian distribution. By conditioning on θ_i and Δ_i , Z becomes the sum of two independent Gaussian distributed random variables. Therefore, by un-conditioning the distribution of random variable, Z can be written as

$$F_Z(z) = E_Y(G(z, 0, Y)) \quad (\text{B.4})$$

where G is the distribution function of a Gaussian random variable with zero mean and variance Y . Y is the conditional variance of Z , given θ_i and Δ_i , and is given by

$$Y = E(Z^2) = 2P_1NT^2[\Delta_1^2 + (1 - \Delta_1)^2](\cos(\theta_1))^2 \quad (\text{B.5})$$

where Δ and θ are uniformly distributed random variables in $[0,1]$ and $[-\pi, \pi]$ respectively. The distribution function for the random variable W is defined as

$$W = \frac{Y}{2P_1NT^2} \quad (\text{B.6})$$

This distribution function can be calculated as

$$F_W(x) = \begin{cases} 1 & x < 0 \\ 1 - \frac{2}{\pi} \int_0^1 \arccos\left(\sqrt{\frac{2x}{1+u^2}}\right) du & 0 \leq x \leq \frac{1}{2} \\ 1 - \frac{2}{\pi} \int_{\sqrt{2x-1}}^1 \arccos\left(\sqrt{\frac{2x}{1+u^2}}\right) du & \frac{1}{2} \leq x < 1 \\ 1 & x \geq 1 \end{cases} \quad (\text{B.7})$$

Therefore the random variable Z has a compound Gaussian distribution whose variance has the distribution given by $F_1(v) = F_w(v/\alpha_1\beta)$ where

$$\beta = 2P_0NT^2 \text{ and } \alpha_1 = P_1/P_0.$$

In the case of multiple interferers, the extension of the above model to the general case of multiple interference is straight forward.

Vector Z is the sum of a set of independent Gaussian distributed vectors for a specific set of phases, θ_i and Δ_i , and its variance is given by

$$Y = \beta \sum_{i=1}^K \alpha_i [\Delta_i^2 + (1 - \Delta_i)^2] [\cos(\theta)]^2 \quad (\text{B.8})$$

where the α_i are the relative powers of the K interfering signals; $P_i = \alpha_i P_0$. The distribution of Y is obtained as the convolution of a set of distributions having the form given in equation (B.10).

$$F_Z(z) = \int_0^{\infty} G(z, 0, \nu) dF_V(\nu) \quad (\text{B.9})$$

where

$$F_V(.) = F_W\left(\frac{.}{\alpha_1 \beta}\right) \otimes F_W\left(\frac{.}{\alpha_2 \beta}\right) \otimes \dots \otimes F_W\left(\frac{.}{\alpha_K \beta}\right) \quad (\text{B.10})$$

Now as we can see from above expressions, if α_i are large and considerably different from each other, $F_V(.)$ is widely spread probability distribution. In other words, the variance of interference can not be approximated accurately by its mean value.

Appendix (C)

Equivalent bandwidth technique and its application in admission control

Equivalent bandwidth is a recently developed technique for admission control in ATM switches (with or without buffer). When traffic parameters are known, effective bandwidths can be calculated and may be used to obtain a circuit switched style call acceptance and routing algorithm for ATM networks. The important feature of the effective bandwidth of a source is that it is a characteristic of that source and acceptable loss probability only. Thus, the effective bandwidth of a source is independent of both the number of sources sharing the buffer and the model parameters of other types of sources sharing the resources.

Because there is considerable functional similarity between an ATM switch without buffer and a CDMA base station, the main aspects of equivalent bandwidth technique as it is applied in admission control for buffer less shared resources are outlined in this appendix.

B.1 Equivalent bandwidth for unbuffered shared resource

Consider N users sharing a buffer-less server with a total capacity of C. Then the probability of overflow can be written as

$$Prob(Overflow) = prob\left(\sum_{i=1}^N U_i > C\right) \quad (C.11)$$

where U_i is the capacity requirement of the user "i" $i = 1, 2, \dots, N$.

In a wireless environment, the random variable U_i can be the users power level or bit rate, and C can be defined as the total interference limit in the cell or total available bandwidth.

The equivalent bandwidth theory primarily uses the Chernoff bound for the overload probability to find a set of control indices (equivalent bandwidth indices) for the user capacity demand that allows a simple circuit switching admission control to be carried out. This idea is explained as follows.

Denoted by $M_i(s)$, the moment generating function of user U_i where $M_i(s) = E[\exp(sU_i)]$ and $E[\cdot]$ is the average operator.

The following inequality can be derived from the Chernoff bound definition:

$$\log(\text{Prob}(\text{Overflow})) \leq -F_N(s^*) \quad (\text{C.12})$$

where

$$\begin{aligned} F_N(s) &= sC - \sum_{i=1}^N \log M_i(s) \\ F_N(s^*) &= \sup_{s \geq 0} (F_N(s)) \end{aligned} \quad (\text{C.13})$$

It has been proven that modeling user capacity demand by an ON-OFF Markovian random variable (with the same average and maximum values as original traffic source) provides a universal upper bound for the overload probability [41]. Therefore, assuming an ON-OFF model for U_i in calculating the Chernoff upper bound is a conservative approximation. According to this assumption, the PDF of a user capacity demand can be written as

$$\begin{aligned} w_i &= \text{Pr}(U_i = c_i) \\ 1 - w_i &= \text{Pr}(U_i = 0) \end{aligned} \quad (\text{C.14})$$

where c_i is the value of the random variable U_i when it is in ON state.

Calculating the moment generating functions $M_i(s)$ using the ON-OFF model will result in the following expression for $F_N(s)$:

$$F_N(s) = sC - \sum_{i=1}^N \log \{1 - w_i + w_i \exp(sc_i)\} \quad (\text{C.15})$$

And s^* in Eq(C.3) can be obtained by solving the following equation:

$$\sum_{i=1}^N \frac{w_i \cdot c_i \cdot \exp(sc_i)}{1 - w_i + w_i \exp(sc_i)} = C \quad (\text{C.16})$$

Assuming that N users can be grouped into J statistically similar classes with $(K_j, j = 1:J)$ sources in each class of traffic, then equation C.6 can be re-written as follows:

$$\sum_{i=1}^J \frac{K_j w_i \cdot c_i \cdot \exp(sc_i)}{1 - w_i + w_i \exp(sc_i)} = C \quad (C.17)$$

The admissible set is defined by a user vector $\mathbf{K} = [K_1 \ K_2 \dots K_J]$ where the overload probability calculated in equation C.1 is below a target value of L where K_i is the number of users from class i traffic. Vector $\mathbf{K}$ can be calculated in terms of a moment generating functions as follows:

$$A_L(C) = \left\{ \mathbf{K} : F_{\mathbf{K}}(s^*) \geq \log\left(\frac{1}{L}\right) \right\} \quad (C.18)$$

For a wide variety of conditions, the boundary of the admissible set, denoted by ∂A_L , is closely approximated by an appropriately chosen linear hyper-plane. The equation of this hyper-plane can be calculated as

$$\partial A_L = \left\{ \widehat{\mathbf{K}} : \sum_{j=1}^J K_j e_j \leq C \right\} \quad (C.19)$$

The parameters e_j are obtained as

$$e_j = \frac{\log M_j(s^*)}{s^* + \frac{(\log L)}{C}} \quad (C.20)$$

The quantity e_j is called the effective bandwidth of class j traffic sources. For obvious reasons, an admission policy that admits a new user if the capacity function G , which is defined in equation (C.11), is smaller than C guarantees that the overload probability for all traffic sources in the system remains below target values.

$$G = \sum_{j=1}^J K_j e_j \quad (C.21)$$

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IMAGE EVALUATION TEST TARGET (QA-3)

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