Power Control in Multimedia CDMA Cellular Networks

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ABSTRACT

Wireless mobile communication is witnessing a rapid growth in, and demand for, improved technology and range of information types and services. Further, third generation cellular networks are expected to provide mobile users with ubiquitous wireless access to a global backbone architecture that carries a wide variety of electronic services. We examine the topic of power control and models that are suitable for modern third generation wireless networks. CDMA technology is proving to be a promising and attractive approach for spectrally efficient, economical and high quality digital communications wireless networks. This thesis addresses the challenge of integrating heterogeneous transmitting sources with a broad range of Quality of Service characteristics in the cellular CDMA networks. Provided the right power control can be devised, CDMA offers the potential of extracting gain from the statistical multiplexing of such sources. A distributed power control algorithm is proposed which is required to update the transmitted power of the mobiles in each of the service classes locally, and enhance the performance of the system significantly. Algorithms for pragmatic issues like power level quantization and truncation of power are derived and incorporated into the proposed distributed power control algorithm.

PREFACE

The research work in this thesis was performed, during the period February 1999 to December 2000, by Miss Neeru Sharma under the supervision of Prof. Fambirai Takawira in the School of Electrical and Electronic Engineering at the University of Natal, Durban, South Africa. This work was partially supported by Alcatel Altech Telecomms and Telkom South Africa as part of the Centre of Excellence Programme at the Centre for Radio Access Technologies.

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The whole thesis, unless specifically indicated to the contrary in the text, is the student's original work, and has not been submitted in part, or in whole to any other University for degree purposes.

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LIST OF ACRONYMS

3G	: Third Generation
AMPS	: Advanced Mobile Phone System
ARIB	: Association for Radio Industry and Business
ARQ	: Automatic Retransmission Request
ASPC	: Adaptive Step Power Control
ATM	: Asynchronous Transfer Mode
B-ISDN	: Broadband Integrated Services Digital Networking
BCH	: Bose-Chaudhuri-Hocquenghem
BER	: Bit Error Rate
BPSK	: Binary Phase Shift Keying
CBR	: Constant Bit Rate
CDMA	: Code Division Multiple Access
CRP	: Constant Received Power
CSOPC	: Constrained Second-Order Power Control
CT-2	: Cordless Telephony-2
CTX	: Continuous Transmission
DB	: Distributed Balancing
DCPC	: Distributed Constrained Power Control
DECT	: Digital European Cordless Telephony
DPC	: Distributed Power Control
DS-CDMA	: Direct Sequence Code Division Multiple Access
DSP	: Digital Signal Processing
DTX	: Discontinuous Transmission
Downlink	: Link from base station-to-mobile
EDGE	: Enhanced Data Rates for Global Evolution
ETSI	: European Telecommunications Standards Institute

ETRI	: Electronics and Telecommunications Research Institute
FDMA	: Frequency Division Multiple Access
FEC	: Forward Error Correction
FER	: Frame Error rate
FH-SS	: Frequency-Hopping Spread-spectrum
FM	: Frequency Modulation
FSPC	: Fixed Step Power Control
Forward Link	: Link from base station-to-mobile
GPRS	: General Packet Radio Service
GSM	: Global System for Mobile Communications
IC	: Interference Cancellation
IMT-2000	: International Mobile Telecommunications-2000
IP	: Internet Protocol
ISDN	: Integrated Services Digital Network
ITU	: International Telecommunications Union
Intercell Interference	: Interference from mobiles located outside the cell of interest
Intracell Interference	: Interference from mobiles located within the cell of interest
LAN	: Local Area Network
LMMSE	: Linear Minimum Mean Square Error
LPI	: Low Probability of Interception
MBS	: Mobile Broadband Systems
MAN	: Metropolitan Area Network
MC-CDMA	: Multi-Carrier Code Division Multiple Access
MUD	: Multiuser Detection
PBX	: Private Branch Exchange
PCB	: Power Control Bit
PDC	: Personal Digital Cellular

PDF	: Power Density Function
PIC	: Parallel Interference Cancellation
QI	: Quality Indicator
QoS	: Quality of Service
QPSK	: Quadrature Phase Shift Keying
RAP	: Radio Access Ports
RSSI	: Received Signal Strength Indicator
Reverse Link	: Link from mobile-to-base station
SIC	: Successive (Serial) Interference Cancellation
SIR	: Signal-to-Interference Ratio
SSMA	: Spread-Spectrum Multiple-access
TDMA	: Time Division Multiple Access
TH-SS	: Time-Hopping Spread-Spectrum
UMTS	: Universal Mobile Telecommunications System
UPCN	: Universal Personal Communications Network
Uplink	: Link from mobile-to-base station
VBR	: Variable Bit Rate
WAN	: Wide Area Network
WCDMA	: Wideband Code Division Multiple Access
WCPN	: Wireless Customer Premises Networks

CHAPTER 1

INTRODUCTION

With the current rapid growth of technology, it can emphatically be said that the objective of today's communication engineers to achieve a global "Universal Personal Communications Network" (UPCN), which was yesterday's myth (before 1980), is tomorrow's reality (beyond 2000) – a world in which any person can access a vast array of near-instant services and information types, or communicate with any other person, at any place and any time, through any medium using only a single hand-held wireless terminal. This world of telecommunications is very much driven by the concept of a wired backbone superhighway infrastructure that is accessed via local wired and wireless access networks. The wired backbone infrastructure will merely be a natural evolution and merging of the existing local-area, metropolitan-area, wide-area (LAN, MAN, WAN), Internet and telephony networks to support a wide variety of services over a single network infrastructure. This infrastructure, in future, may consist mainly of high bandwidth fiber-optic cables and satellite systems supporting transmission standards such as Internet Protocol (IP), Broadband Integrated Services Digital Networking (B-ISDN) or Asynchronous Transfer Mode (ATM).

Until recently, this notion of a global UPCN had been thought to be impractical due to the daunting scale of the system, the extremely large bandwidth requirements, and the challenges associated with integrating different services with contrasting transmission requirements. However, recent advances in the fields of information coding, signal processing, information compression and modulation techniques that attempt to compress as many bits of information as possible into a unit bandwidth, and fiber-optic transmission mediums, which provide large bandwidths have placed a viable solution to the UPCN within a tangible grasp.

1.1 Background to Wireless Personal Communication Systems

The objectives of the research and development of the Third Generation (3G) Wireless Personal Communication Systems are focused in three technological platforms, namely, International Mobile Telecommunications-2000 (IMT-2000), Mobile Broadband Systems (MBS), and Wireless Customer Premises Networks (WCPN). IMT-2000 is a multi-function, multi-service, multi-application digital system, evolving from currently operational second generation systems.

The *first generation* of mobile communications systems was characterized by analog transmission of voice only, and had severe capacity limitations. An example of a first generation application for wireless cellular telephony is the Advanced Mobile Phone System (AMPS), which offered 666 analog FM channels (42 control and 624 voice channels) [Goodman, 1990]. The conversion from analog to digital allowed for improved time division multiplexing techniques, increased network capacity and the inclusion of digital error detection and correction schemes.

A variety of *second generation* networks accrued as a result [Goodman, 1991], all dedicated to supporting digital voice only but designed for different operating environments. Throughout the world, several predominant second generation cellular voice standards have emerged such as: IS-54 (Digital-AMPS), Global System for Mobile Communications (GSM, European origin), IS-136 (North American Digital Cellular), Personal Digital Cellular (PDC, Japan), and IS-95 CDMA (USA, Asia Pacific countries). For cordless telephony and wireless PBX applications, the Digital European Cordless Telephony (DECT indoor and outdoor) and indoor Cordless Telephony standard-2 (CT-2), standards have been successfully deployed throughout the world. An unfortunate consequence of this multiplicity of standards is that they offer very little inter-compatibility, each require specific hardware (separate mobile terminals for each standard), and are designed for different cell dimensions and population sizes.

The sudden explosion of the Internet and World Wide Web over the last few years has prompted an increased demand for Internet connectivity in both wired and wireless domains. *Third generation* wireless networks are deemed to support a vast variety of information types, operate in all transmission environments and be capable of supporting a large population with a highly dynamic profile. Unlike first and second generation networks which are designed for cell sizes of several kilometers, third generation networks are likely to consist of cells which are several orders of magnitude smaller. This allows densely populated metropolitan areas to be serviced with a higher capacity. In order for third generation access networks to be a success, a standard must be specified to allow global inter-compatibility and inter-networking. Only very recently, with the need and demand for third generation systems continually increasing, have researchers started striving for a common global standard that will be able to meet these requirements. Presently, the third generation cellular standards of choice appear to be IMT-2000. The standards for the Universal Mobile Telecommunications System (UMTS) are being standardized by European Telecommunications Standards Institute (ETSI). UMTS belongs to the IMT-200 family and whilst supporting existing services, will be capable of offering new and revolutionary services including multimedia and access to Internet offering a speed of 2 Mbits/s for a single user at a radio access network. The other candidate access protocol standards for IMT-2000 appear to be cdma-2000 and Wideband CDMA (WCDMA), which is a wideband evolution of the IS-95 CDMA standard. All these systems are being designed with stringent inter-compatibility, a high degree of worldwide design commonality, wide roaming, and a large array of high quality services in mind. The IMT-2000 family concept opens way for recognition of differences while exploiting similarities. The evolution of mobile communications is tabulated in Appendix A.1.

In wireless networking comes a vast array of new challenges. In contrast to wired networks, the properties of wireless channels are highly unpredictable and time varying. At low transmission frequencies, signal propagation is most penetrative, but practical antennae sizes become the limiting factor. At high frequencies, radio signals are more easily received but the propagation of the signal is strongly influenced by many factors such as: the distance between the transmitter and receiver, the geographical obstructions and terrain over and through which the signal traverses (responsible for fading, multipath distortion, and shadowing of the signal), and interference from adjacent signals operating in the same frequency band. In a mobile environment, some of these effects are slowly time varying, while others may be rapidly time varying.

1.2 Multimedia Networking

A significant problem that has faced communications engineers over the years is that of efficiently integrating a multitude of different services with diverse traffic profiles and contrasting Quality of Service (QoS) requirements on to the same communications medium. Examples of such services might be: text, e-mail, digitized voice (telephony), video, video telephony and video conferencing, music on demand, World Wide Web pages, data files and control data (signaling). The QoS is the end-user's qualitative evaluation of the ease and quality of communication in the network. The QoS requirements specify factors such as the information transmission rate, maximum acceptable bit error rate, end-to-end delay constraints, delay variation constraints and call blocking/dropping probabilities.

In a typical voice telephony service, the transmission requirements for *digital voice* may be listed as follows. Digital voice, generally, require a relatively low bit transmission rate; typically in the range 4kbits/s to 64kbits/s, depending on the quality requirements and voice coding scheme. In order to ensure a real-time, fluent conversation, there must be a very low end-to-end delay with a minimal variation in delay. Finally, voice can tolerate moderately high bit error rates without the need to retransmit corrupt information. A typical *video telephony* or video on demand service would have similar requirements, although the bit transmission rates would need to be a lot higher due to the inclusion of visual information (28kbits/s up to several Megabits/s depending on the image resolution and quality, frame rate, depth of colour, and video compression technique). Traditionally, services that have stringent delay constraints, such as voice traffic, have been classified as *real-time services*.

In direct contrast, a *data service* such as e-mail or a Web browsing can generally tolerate moderately high end-to-end transmission delays with large variations in the end-to-end delay, but requires very low bit error rates and generally requires the retransmission of any corrupt or irrecoverable information. Also, depending on the type of service, data bit rate requirements can vary dramatically. A bit rate of 1kbit/s might be sufficient for the transmission of small text files or e-mail, but is grossly inadequate for the transmission of large data files exceeding several Megabytes in size. Time non-critical data services are usually referred to as *non real-time services*.

Efforts in the field of integrated services networking have been in standards such as Integrated Services Digital Networking (ISDN), ATM, IP and, more recently, UMTS belonging to the IMT-2000 family. These standards provide structured protocols for supporting a large variety of information types with diverse characteristics and transmission requirements.

The IMT-2000 family has adapted CDMA as the air interface. CDMA has enjoyed a tremendous growth worldwide, especially over the last two years. The subscriber counts and growth rates show that cdmaOne cellular standard (official brand name for the IS-95 CDMA standard) is fast becoming the dominant choice for second generation digital communications in many countries, and has found tremendous commercial application worldwide. A key reason, amongst others, why CDMA has become popular is that inherent in CDMA systems are several properties that are highly beneficial to cellular mobile networks. These include higher spectral reuse efficiency, greater immunity to multipath fading, gradual overload capability, simple exploitation of sectorisation, encryption, lower transmission power requirements and more robust handoff procedures [Lee, 1991], [Kohno, Meidan & Milsein, 1995]. Until recently, CDMA has been significantly more difficult to implement than conventional narrowband TDMA and FDMA. However, the advent of sophisticated digital signal processing (DSP) hardware, improved power control schemes, and improved receiver structures (e.g. RAKE and Multiuser Detector based receivers) have narrowed this implementation gap significantly.

1.3 Focus and Goals of the Thesis

Although CDMA has received much literary attention for first and second generation voice cellular systems as well as data-only networks, considerably less research has been done on power control for integrating multiple services using CDMA as an underlying system. The work that has appeared either mainly focuses on power control in a single service CDMA system or has described power control schemes that are somewhat elementary or idealized. The research this thesis presents is motivated by the evolution of mobile communications towards global support of multimedia services and the somewhat lacking amount of work done in the field of power control for CDMA radio networks at the time of commencement of this project.

The focus of the thesis falls on the study of power control and the derivation and evaluation of a power control scheme based on Quality-of-Service (QoS) for a multi-cellular CDMA wireless access network supporting data, voice and video traffic. The goals of this research are two-fold. The first goal is to contribute to the field of power control. To this end, we aim to derive a new scheme that improves in some way on the performance of existing schemes which are either based on centralized wireless networks employing single service CDMA or use a conventional fixed step for power update. The second goal is to derive schemes for some pragmatic issues in power control and finally incorporate these schemes into a multicellular and multiservice CDMA system. Simulation models are useful for obtaining quick predictions of the performance of a system, prior to the actual implementation of the system. Hence, a simulation model is developed, not only to evaluate the performance of the power control scheme, but also to validate the results and approach of the proposed scheme.

It is well known that the practical capacity, or multiple access capability of CDMA is interference limited [Gilhousen, Jacobs, Padovani, Viterbi, Weaver & Wheatley III, 1991], [Viterbi & Viterbi, 1993], [QUALCOMM Report, 1992].

This is particularly true in a system such as IS-95 system that uses conventional matched filter receivers instead of optimal multi-user receivers. It is therefore particularly important that power control be applied in order to increase system capacity.

To achieve a considerable capacity, all signals, irrespective of the distance should arrive at the base station with the same mean power; therefore, the performance of the transmitter power control is one of the several dependent and inevitable factors when deciding the performance of a CDMA system. The concept of *Signal-to-Interference ratio (SIR) balancing* for power control is an optimal solution in the sense that the minimum SIR of all the communication links is maximized [Zander, 1992a], [Grandhi, Vijayan, Goodman & Zander, 1993]. A literature review on the existing power control schemes for single service CDMA networks revealed two fundamental approaches. The first is the centralized scheme, i.e., the base station has full control over channel access in the network [Grandhi, *et al.*, 1993]. The second is the distributed schemes, which are important in the sense that they alleviate the signaling burden at the base station controller [Foschini & Miljanic, 1993], [Grandhi, Vijayan, Goodman, 1994]. In this thesis, the advantages and disadvantages of these schemes are examined, and a *novel* power control scheme for a multimedia CDMA network that implements distributed scheme is derived. We name our proposed scheme "Distributed Variable Step Size Power Control Scheme for Multimedia CDMA networks".

1.4 Thesis Layout

There are eight chapters in this thesis. Chapter 1, this chapter, introduced the concepts, challenges and future requirements of a global information infrastructure incorporating the next generation of wireless networks required to provide ubiquitous access to such an infrastructure. The focus and goals, and the motivation for this thesis research were also presented.

In Chapter 2, we present an overview of CDMA cellular systems and their evolution towards the wideband CDMA network. The Chapter gives a comprehensive introduction to CDMA, describing in detail its concepts and basic elements. We describe the features of the IS-95 CDMA air interface according to the new IS-95B standard, with a focus on the new downlink and uplink channel structures. Finally, we provide a brief introduction to wideband CDMA that has emerged as the mainstream air interface solution for the Third Generation networks. We also compare the parameters of WCDMA in Europe and Japan, cdma2000 in the United States, and wideband CDMA in Korea.

Chapter 3 is a literature survey on traditional power control schemes, with particular focus on those relevant for single-service CDMA networks. A general model of power control is described and the main aim of power control is presented. This is followed by an explanation of the different types of power control schemes that can be categorised as: open loop, closed loop, centralized or decentralized schemes. A framework model for power control identifying the dominant factors and channel quality criteria such as: signaling and modulation schemes, link orientation, environment morphology and topology, speed of mobile terminals, cell hierarchy and the connection type, is also discussed. We then give an introduction to the various aspects of power control such as the capacity and load of the system, centralized or distributed power controller, global stability and performance, quality measures, feedback bandwidth, hardware constraints, time delays and the bandwidth of the controller. Thereafter, a discussion on existing power control schemes is presented with a comprehensive survey of centralized power control algorithms, distributed power control algorithms and briefly on those power control schemes, which are implemented in IS-95.

In Chapter 4, we review the various power control schemes for multi-service wireless applications. Factors influencing QoS in multimedia networks are presented. It describes various classes of service that are categorised according to their traffic types in a multimedia network. Power control structures for these classes of service are also given. A detailed survey of the previous proposed power control algorithms in multimedia CDMA network is given at the end of the Chapter.

In Chapter 5, we present in detail our proposed power control scheme for a multimedia CDMA radio network, called "Distributed Variable Step Size Power Control Algorithm". Particular emphasis is placed on the derivation of the model of the power control algorithm. As will be discussed, this distributed power control algorithm is required to update the transmitted power of the mobiles in each of the service classes. The received power and the Signal-to-Interference ratio for each of the service classes are adapted locally based on the measurements of the mean and the variance of the interference caused by the other active mobiles. The SIR values are tailored to provide different QoS degrees in the multicellular and multiservice CDMA system. The Chapter describes the workings of a software simulator that is used to generate simulation results for the proposed power control scheme. We first discuss the cellular structure followed by the description of the event-driven software simulator. Finally, we present a comparison of our proposed scheme with other similar power control schemes proposed in the literature, and quantify the performance enhancements that can be gained through the application of our variable step size power control algorithm.

In Chapter 6, we extend our proposed power control scheme to incorporate two important issues, namely, truncation of transmit power and power level quantization, in the CDMA communication system. The effects are addressed and schemes for each of these issues are derived and their performance analyzed. We present the network model and the simulation model for both these issues. Our proposed model for truncation is loosely based on the scheme proposed by the authors Kim and Goldsmith [2000]. We diverge from the aforementioned model in that: (1) we incorporate multiservices, and (2) our scheme compensates for deep fades. The transmission power level can take on any positive real values. However, in practice, some restrictions are inevitable, though the system capacity deteriorates. We present two quantization level schemes for the variable step size power control algorithms. Results of the performance of both our schemes, i.e., the transmit power truncation and power level quantization are presented and compared to the similar schemes proposed in the literature. Results are also compared to those obtained when both truncation and quantization techniques are not employed into the system.

Chapter 7 reviews on a study done on the control theoretic approach to power control. For practical reasons, it is necessary to control powers in a distributed fashion. Work presented by Gunnarsson [2000] shows that these distributed algorithms, which can be seen as interconnected local control loops, can be considered separately with respect to dynamical behaviour. Previous proposals are seen to fall into any two categories: Algorithms based on *information feedback* are associated with a linear local loop, which can be analyzed with methods from linear systems theory, and conversely, *decision feedback* algorithms are not solely linear, but rather linear with a static nonlinear component. Such control loops can be approximately analyzed using discrete-time describing functions.

Finally, Chapter 8 presents the research conclusions and some recommendations are made for further study.

1.5 Original Contributions in this Thesis

The *original contributions* in this Thesis may be summarised as follows:

1 The derivation of a novel power control scheme for a multimedia CDMA radio network (presented in Chapter 5). The originality of our scheme lies in the implementation of the power control scheme in which the transmitted powers of the mobile users belonging to any class of service are updated using a step size that is calculated locally. It helps in the fast convergence of the powers to their required levels.

2 The derivation of the SIR Adaptation Algorithm (presented in Chapter 5), which characterises the mobiles belonging to different service classes by distinctive QoS parameters consisting of the desired minimum SIR level to be satisfied. The received power and SIR for mobiles in each of the service classes are adapted based on the measurements of the mean and the variance of the total interference caused by all the other active mobiles.

3 The derivation of a truncated power control scheme for the variable step size power control algorithm (presented in Chapter 6), which sets a threshold for the maximum power transmission of a mobile in a multimedia CDMA network compensating for low gains also.

4 The derivation of a power level quantization scheme for the variable step size power control algorithm (presented in Chapter 6), which quantizes the power levels of the mobile users in the variable step size power control algorithms by a fixed level and a variable level.

Parts of the research presented in this Thesis have been presented by the author at the following local and international conferences:

1 Sharma, N & Takawira, F, (1999), "A Distributed Variable Step Size Power Control Algorithm for Different Classes of Service", *Proceedings of SATNAC'99 Conference*, Durban, South Africa, pp.38-42, September 1999.

2 Sharma, N & Takawira, F, (2000), "Performance of SIR-Based Distributed Power Control in the Cellular CDMA System with Heterogeneous Traffic Types", *Proceedings of IEEE COMSIG'00 Conference, SATCAM 2000*, Cape Town, South Africa, pp.54-59, September 2000.

CHAPTER 2

CDMA CELLULAR NETWORKS

2.1 Introduction

Recently, extensive investigations have been carried out into the application of the CDMA System. Many research and development projects in the field of Wideband CDMA have been going on in Europe, Japan, the United States and Korea [Chaudhury, Mohr & Onoe, 1999], [Prasad, 1996], [Prasad, 1998], [Zeng, Annamalai & Bhargava, 1999]. Emerging requirements for higher rate data services and better spectrum efficiency are the main drivers identified for mobile radio systems by the International Telecommunications Union (ITU). The main objectives for the air interface can be summarized as:

- Full coverage and mobility for 144Kb/s, preferably 384Kb/s.
- Limited coverage and mobility for 2Mb/s.

- High spectrum efficiency compared to existing systems.
- High flexibility to introduce new service.

The preferred technology for third-generation systems depends on technical, political, and business factors. Technical factors include issues such as provision of required data rates and performance. Political factors involve reaching agreement between standard bodies and taking into account the different starting points of different countries and regions. On one hand, the investments into the existing systems motivate a backward compatibility approach. On the other, new business opportunities or the possibility of the changing current situation might motivate a new approach.

The origins of spread spectrum are in the military field and navigation systems. Techniques developed to counteract intentional jamming have also proved suitable for communication through dispersive channels in cellular applications. During 1980s QUALCOMM investigated DS-CDMA techniques, which finally led to the commercialization of cellular spread spectrum communications in the form of the narrowband CDMA IS-95 standard. During the 1990s wideband CDMA techniques with a bandwidth of 5MHz or more have been studied intensively throughout the world, and several trial systems have been built and tested [Ojanpera, 1997]. These include FRAMES Multiple Access (FRAMES FMA 2) in Europe; Core-A in Japan, the European/Japanese harmonized WCDMA scheme, cdma2000 in the United States and the Telecommunication Technology Association I and II (TTA I and TTA II) schemes in Korea.

2.2 CDMA Concepts

In a CDMA system each user is assigned a unique code sequence it uses to encode its information-bearing signal. The receiver, knowing the code sequences of the user, decodes the received signal after reception and recovers the original data. This is possible since the cross-correlation between the code of the desired user and the codes of the other users is small. Since the bandwidth of the code signal is chosen to be much larger than the bandwidth of the information-bearing signal, the encoding process enlarges the spectrum of the signal and is therefore also known as spread-spectrum modulation. The resulting signal is also called spread-spectrum and CDMA is often denoted as Spread-Spectrum Multiple Access (SSMA) [Gustafsson, Jamal & Dahlman, 1997].

The spectral spreading of the transmitted signal gives to CDMA its multiple access capability, and it is related to the system processing gain. The ratio of transmitted bandwidth to information bandwidth is called the processing gain G:

$$G = \frac{W_t}{W_i} \tag{2-1}$$

where W_t is the transmission bandwidth and W_i is the bandwidth of the information-bearing signal.

Because of the coding and the resulting enlarged bandwidth, the Spread-Spectrum (SS) signals have a number of properties that differ from the properties of a narrowband signals. The most interesting ones, from the communications point of view are:

- Multiple access capability
- Protection against multipath interface
- Privacy
- Interference rejection
- Anti-jamming capability, especially narrowband jamming
- Low probability of interception (LPI – because of its low power density, the spread-spectrum signal is difficult to detect and intercept)

2.2.1 Spread-Spectrum Multiple Access

Direct-Sequence (DS) - In DS-CDMA the modulated information-bearing signal (the data signal) is directly modulated by a digital, discrete-time, discrete-valued code signal.

Frequency Hopping (FH) - In frequency hopping CDMA, the carrier frequency of the modulated information signal is not constant but changes periodically, hopping from frequency interval (called frequency bin) to another in a pseudorandom manner. The hopping pattern is determined by the code signal. The set of available frequencies the carrier can attain is called the *hop-set.* The frequency occupation of an FH-SS system differs considerably from DS-SS system. A DS system occupies the whole frequency band when it transmits, whereas an FH system uses only a small part of the bandwidth when it transmits, but the location of this part differs in time.

Time Hopping (TH) - In time hopping CDMA the data signal is transmitted in rapid bursts at time intervals determined by the code assigned to the user. The time axis is divided into frames and each frame is divided into M time slots. During each frame the user transmits in any one of the M slots. Which of the M slots is used depends on the code signal assigned to the user. Since the user transmits all of its data in one, instead of M slots, this results in a frequency spread by a factor of M.

Hybrid Systems - The hybrid CDMA systems include all CDMA systems that employ a combination of two or more of the above-mentioned spread-spectrum modulation techniques or combination of CDMA with some other multiple access technique. By combining the basic spread-spectrum modulation techniques, we have four possible hybrid systems: DS/FH, DS/TH, FH/TH, and DS/FH/TH; and by combining CDMA with TDMA or multicarrier modulation we get two more: CDMA/TDMA and MC-CDMA. The idea of a hybrid system is to combine the specific advantages of each of the modulation techniques. For example, the combined DS/FH system has the advantage of combining the anti-multipath property of the DS system with the favorable near-far operation of the FH system. The disadvantage lies with the increased complexity of the transmitter and receiver.

2.2.2 Elements of CDMA Cellular Networks

The elements of CDMA cellular systems, which impact on the study of power control are: soft handover, interfrequency handover and multiuser detection.

Soft Handover - In soft handover a mobile station is connected to more than one base station simultaneously. Soft handover is used in CDMA to reduce the interference into other cells and to improve performance through macro diversity. Softer handover is a soft handover between two sectors of a cell. Because of the processing gain, the spatial separation between cells using the same frequencies is not needed in CDMA. Usually, a mobile station performs a handover when the signal strength of a neighboring cell exceeds the signal strength of the current cell by some given threshold. If this handover results in breaking the existing connection then this is called hard handover.

The signal structure of CDMA is well suited for the implementation of soft handover. On the uplink, two or more base stations can receive the same signal because of the reuse factor of one. On the downlink the mobile station can coherently combine the signals from different base stations since it sees them as just additional multipath components. This provides an additional benefit called macro diversity. A separate channel called the pilot channel is usually used for the signal strength measurements for handover purposes.

Interfrequency Handover - The third generation CDMA networks will have multiple frequency carriers in each cell, and hot-spot cells will have a larger number of frequencies than neighboring cells. Furthermore, in hierarchical cell structures, micro cells will have a different frequency than the macro cells overlaying the micro cells. Therefore, an efficient procedure is needed for a handover between different frequencies. A blind handover as used in second generation CDMA systems does not result in an adequate call quality. Instead, the mobile station has to be able to measure the signal strength and quality of another carrier frequency, while maintaining the connection in the current carrier frequency. Since CDMA transmission is continuous, there are no idle slots for the interfrequency measurements. Therefore, compressed mode and dual receiver have been proposed as a solution to interfrequency handover [Gustafsson *et al.*, 1997]. In the compressed mode, measurement slots are created by transmitting the data of a frame, for example, with a lower spreading ratio during a shorter period, and the rest of the frame is utilized for the measurements on the other carriers. The dual receiver can measure other frequencies without affecting the reception of the current frequency.

Multiuser Detection (MUD) –A common receiver implementation in DS-CDMA system is the RAKE receiver. The capacity of a DS-CDMA system using RAKE receiver is interference limited. Practically, when a new user, or interferer, enters the network, other users' service quality goes below the acceptable level. Multiuser Detection (MUD), also called joint detection, provides a means of reducing the effect of multiple access interference, and hence increases the system capacity.

In addition to capacity improvement, MUD alleviates the near-far problem typical to DS-CDMA systems. A mobile station close to a base station may block the whole cell traffic by using too high a transmission power. If this user is detected first and subtracted from the input signal, the others do not see the interference. Since optimal multiuser detection is very complex and in practice impossible to implement for any reasonable number of users, a number of sub-optimum multiuser and interference cancellation receivers have been developed. The sub-optimum receivers can be divided into two categories namely, linear detectors and interference cancellation. Examples of linear detectors are decorrelators and linear minimum mean square error (LMMSE) detectors. Parallel interference cancellation (PIC) and successive (serial) interference cancellation (SIC) are examples of interference cancellation [Ojeanpera & Prasad, 1998].

2.3 IS-95

This section briefly describes the feature of the IS-95 according to the new IS-95 standard with a focus on the new downlink and the uplink channel structure [TIA/EIA-95A, 1995], [TIA/EIA-95B, 1997], [TIA/EIA/IS-97, 1994], [TIA/EIA/IS-98, 1994].

2.3.1 Downlink Channel Structure

The pilot channel, the paging channel and the synchronization channel are common control channels and traffic channels are dedicated channels. A common channel is a shared channel, while a dedicated channel is solely allocated for the use of a single user.

Figures 1-1, 1-2 and 1-3 show self-explanatory figures of the data processing in pilot, synchronization and paging channels respectively.

Figure 1-4 shows the structure of the forward channel. The structure of the forward channel is similar to that of the paging channel. The only difference is that the forward channel contains multiplexed Power Control Bits (PCB).

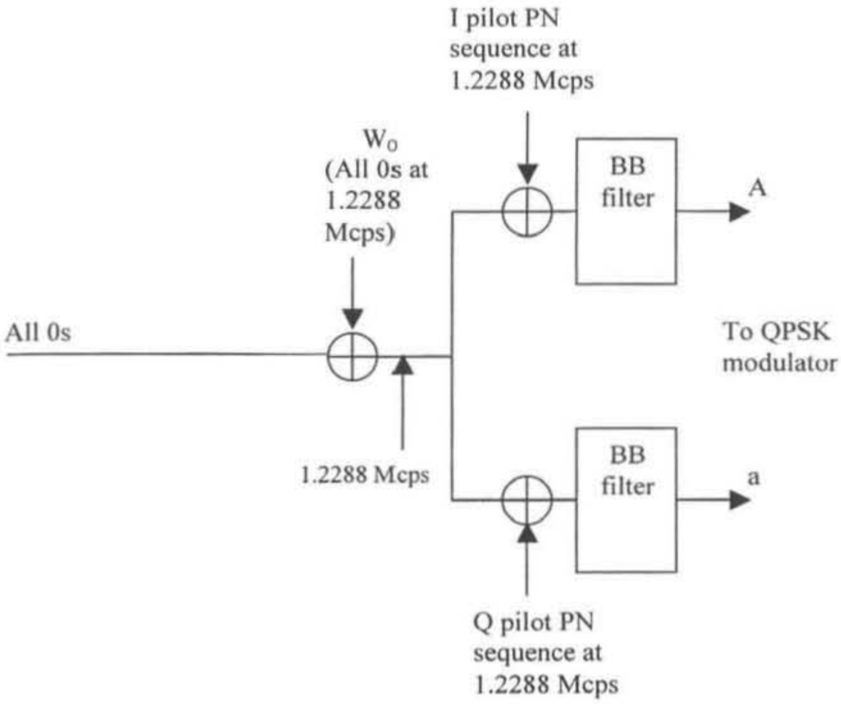

Figure 1-1 Pilot Channel

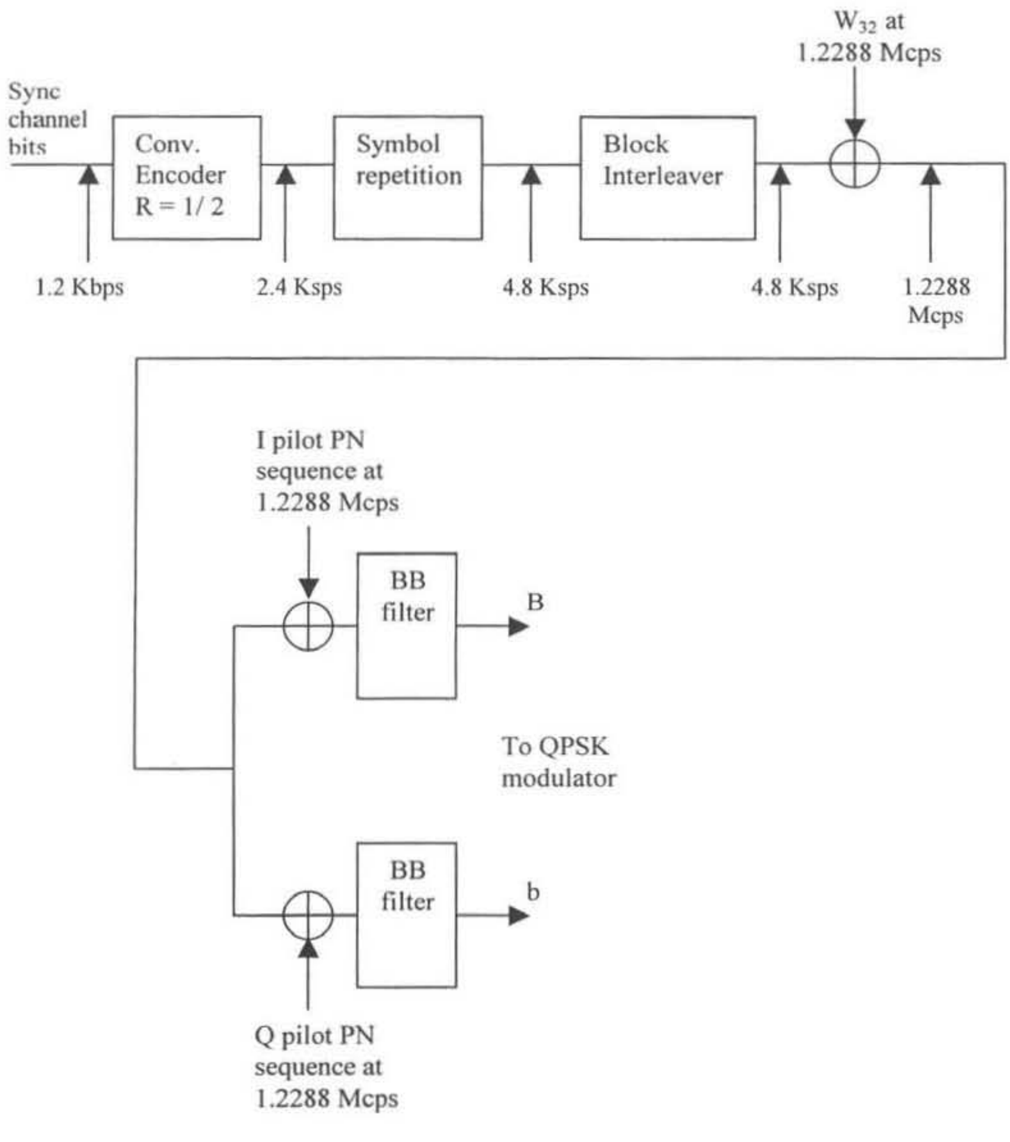

Figure 1-2 Synchronization Channel

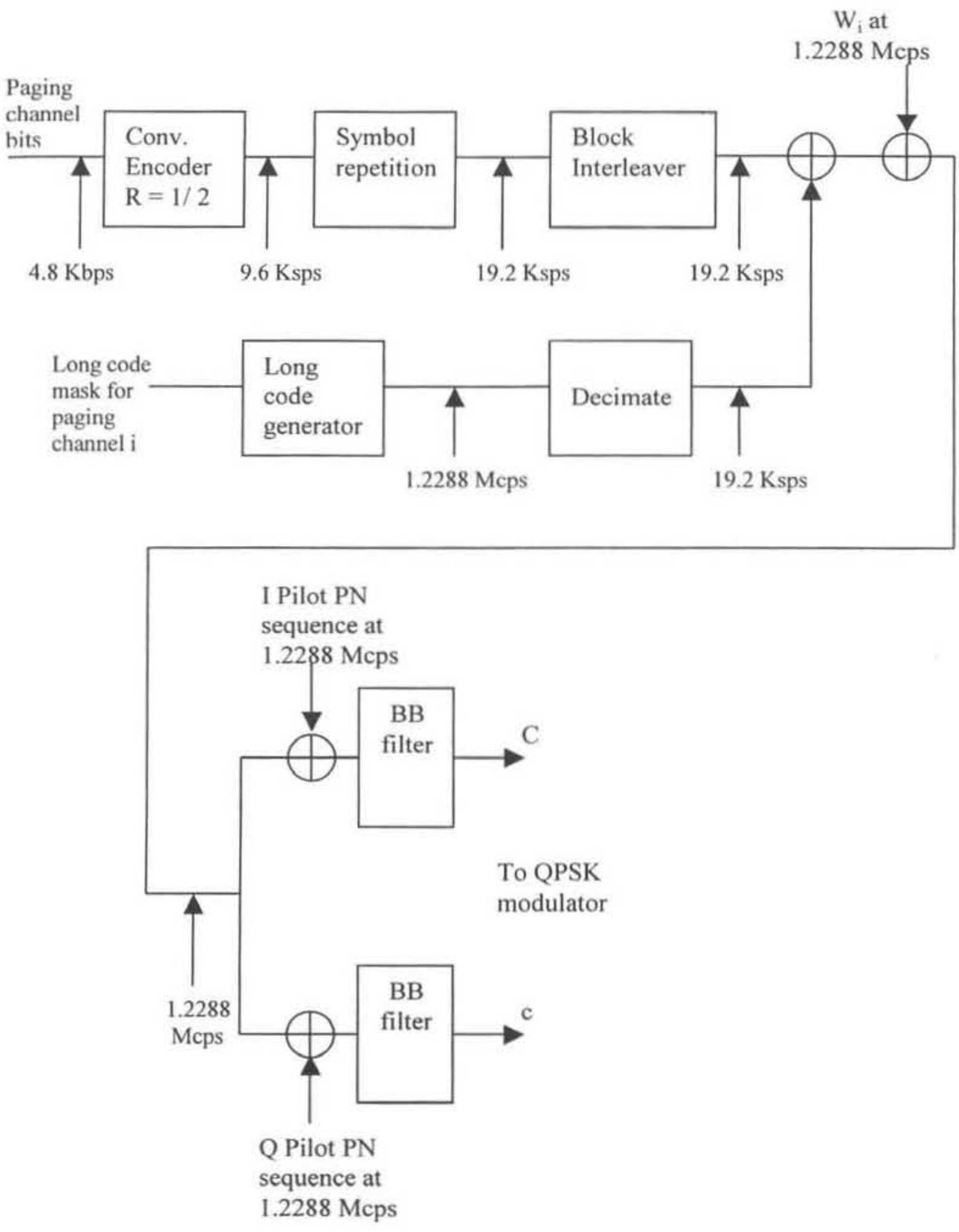

Figure 1-3 Paging Channel

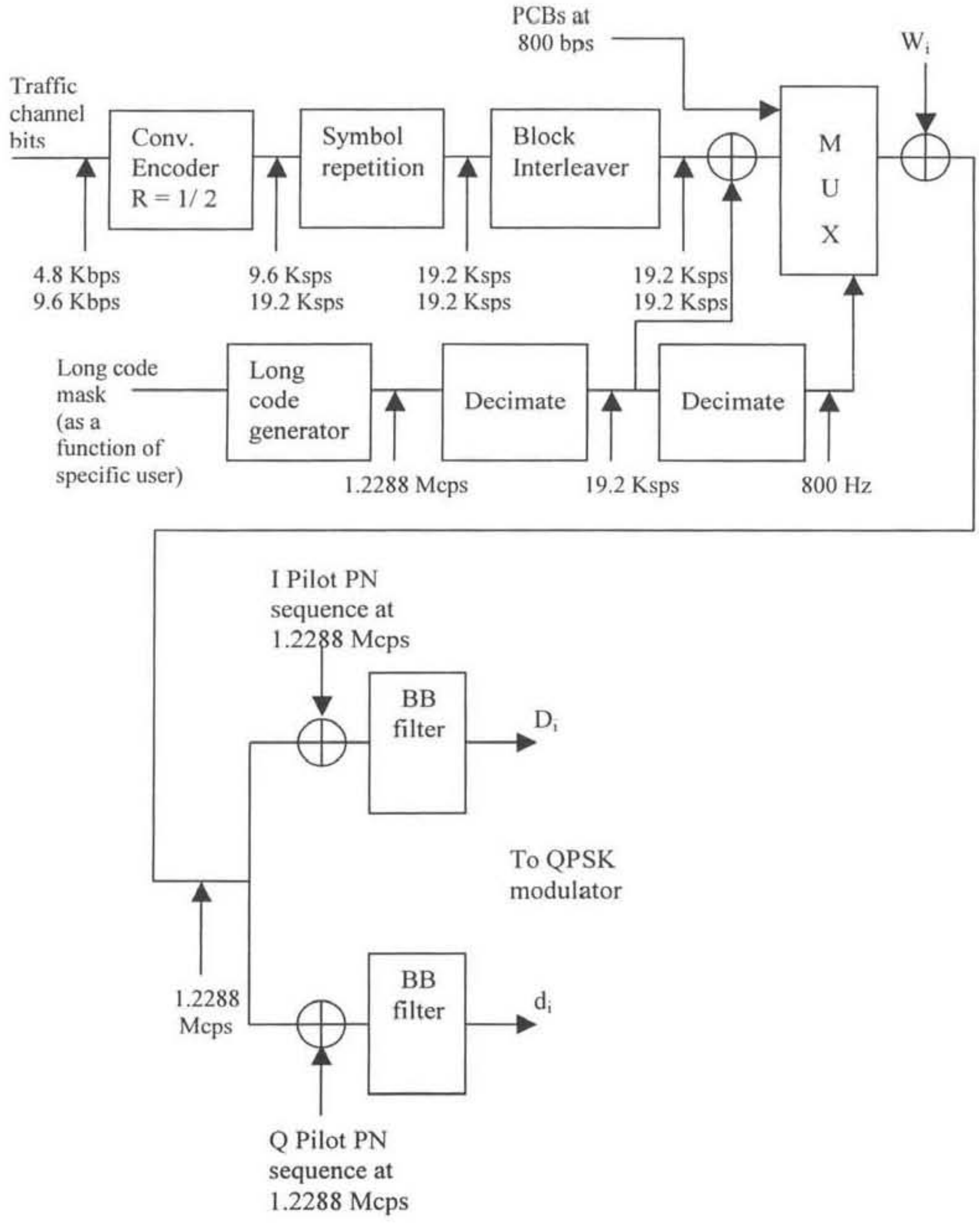

Figure 1-4 Forward Traffic Channel

2.3.2 Uplink Channel Structure

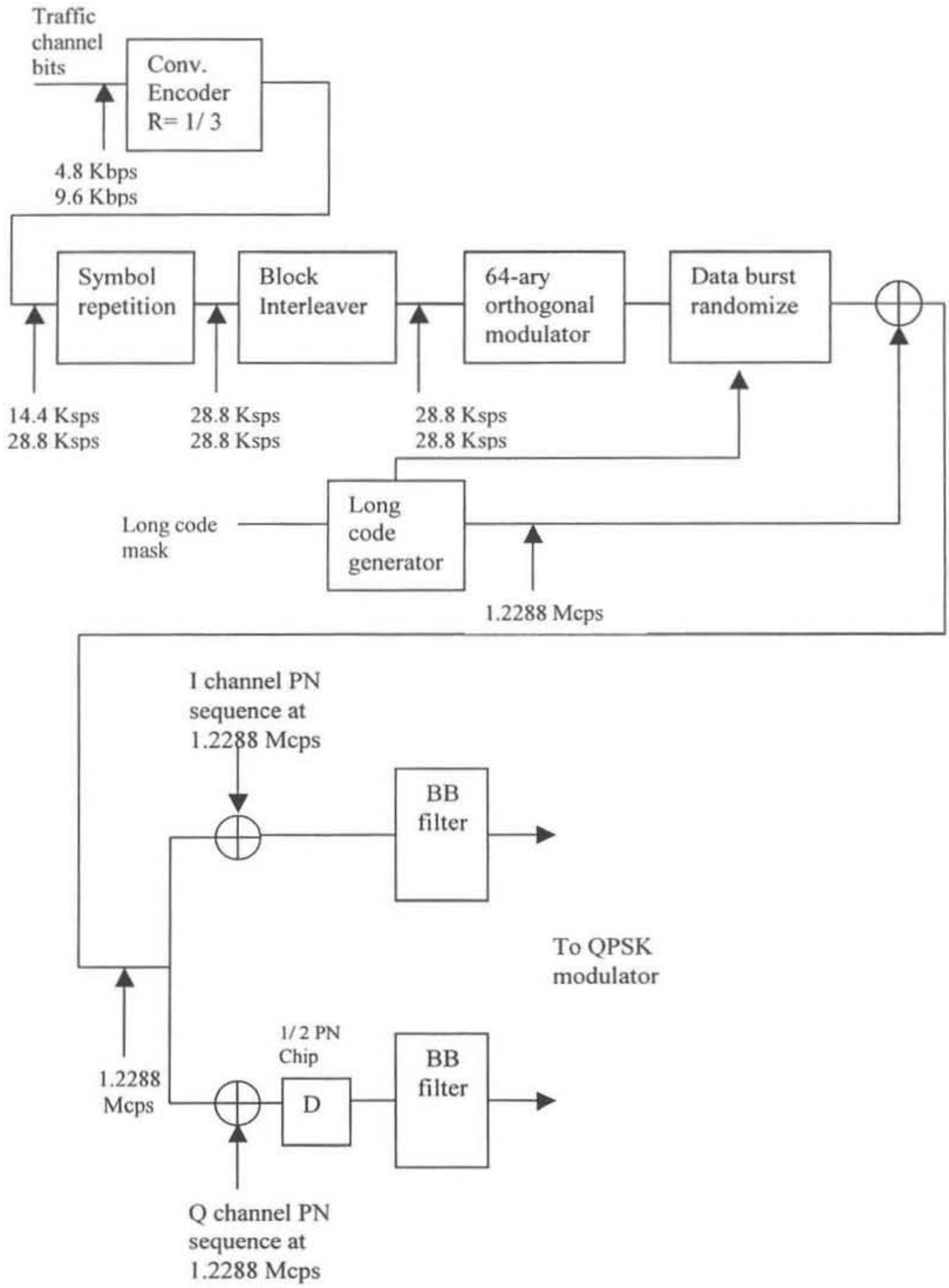

Figure 1-5 Reverse Traffic Channel

The uplink has two physical channels: a traffic channel, which is a dedicated channel, and a common access channel. Data transmitted on the traffic channels are grouped into 20-ms frames, convolutionally encoded, block interleaved, and modulated 64-ary orthogonal modulation. Then, prior to baseband filtering, the signal is spread with a long PN sequence of 1.2288Mc/s, split into I and Q channels, and spread with in-phase and quadrature spreading sequences. This is shown in Figure 1-5.

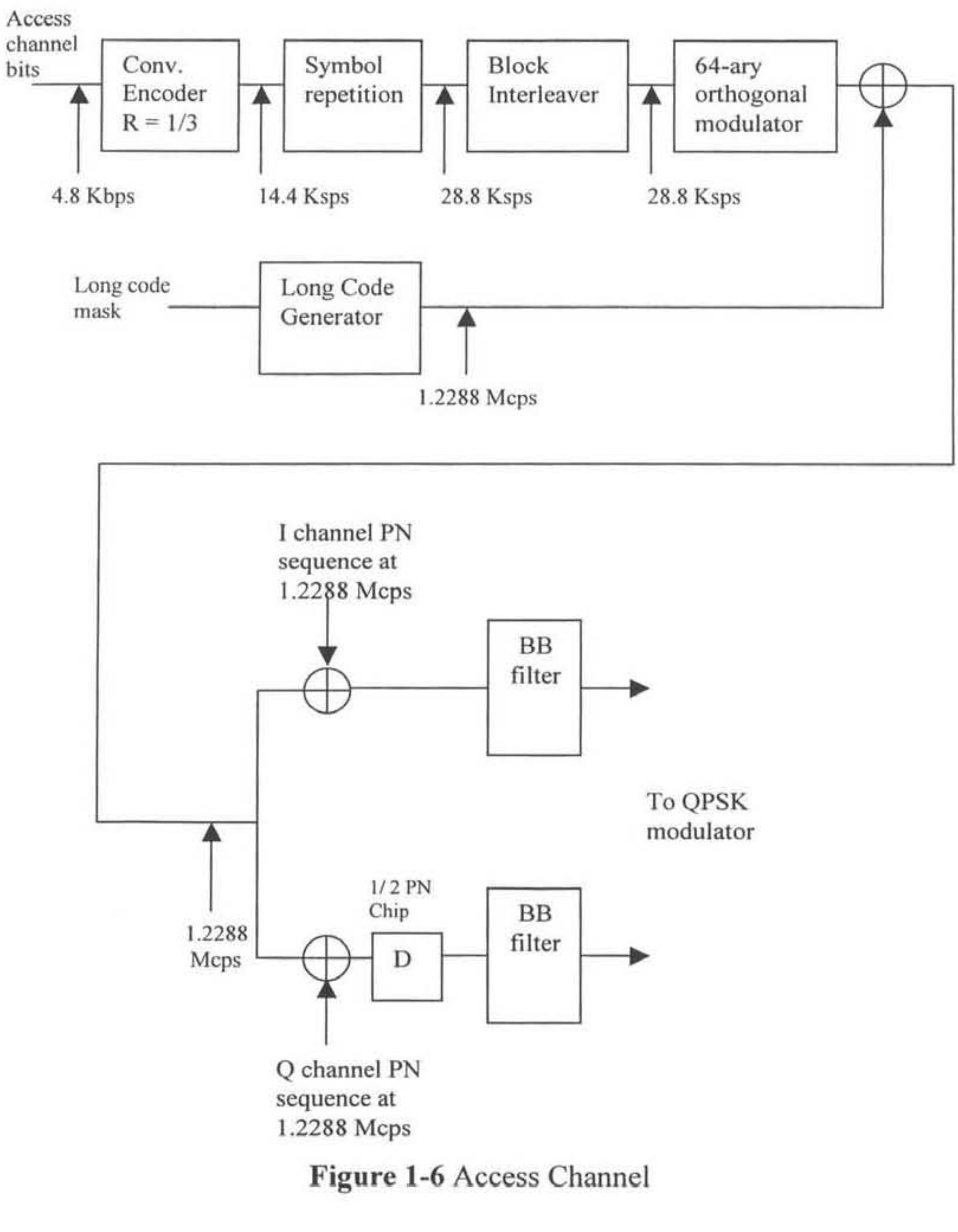

Figure 1-6 Access Channel

The access channel is used by the mobile station to initiate a call, to respond to a paging channel message from the base station, and for a location update. It supports fixed data rate operation at 4.8 Kb/s. Similar to the downlink, code symbols output from the convolutional encoder are repeated before being interleaved as shown in Figure 1-6.

2.4 Air Interface Technologies for Third Generation Systems

In the search for the most appropriate multiple access technology for third-generation wireless systems, a number of new multiple access schemes have been proposed like Wideband CDMA schemes, UWC-136, TDMA-based schemes and TD-CDMA. This section compares the features of some of the CDMA based 3G air interfaces that have been proposed. WCDMA has been developed by the standardization organizations in Europe, Japan, the United States and Korea. In addition to asynchronous CDMA proposals of WDMA in ETSI [ETSI, 1998] and ARBI [ARBI, 1998], T1P1 in the United States has joined the development of WCDMA [T1P1, 1998]. Standardization committee TIA TR45.5 is responsible for the selection of the basic cdma2000 concepts. Korea proposed two CDMA concepts, TTA I and TTA II [TTA, 1998a], [TTA, 1998b].

The third-generation air interfaces can be characterized by the following new advanced properties:

- Provision of multirate services
- Packet data
- Complex spreading
- A coherent uplink using a user dedicated pilot

- Additional pilot channel in the downlink for beamforming
- Seamless interfrequency handover
- Fast power control in the downlink
- Optional multiuser detection

Table 1-1 below compares the parameters of WCDMA and cdma2000.

Features	**WCDMA**	**cdma2000**
Channel Bandwidth	5, 10, 20 MHz	1.25, 5, 10, 15, 20 MHz
Downlink RF Channel Structure	Direct spread	Direct spread or multicarrier
Chip Rate	4.096/8.192/16.384 Mcps	1.2288/3.6864/7.3728/11.0593/ 14.7456 Mcps for direct spread n x 1.2288 Mcps (n = 1,3,6,9,12) for multicarrier
Roll-off Factor	0.22	Similar to IS-95
Frame Length	10 ms/20 ms (optional)	20 ms for data and control / 5 ms for control information on the fundamental channel
Spreading Modulation	Balanced QPSK (downlink) Dual Channel QPSK (uplink) Complex spreading circuit	Balanced QPSK (downlink) Dual Channel QPSK (uplink) Complex spreading circuit
Data Modulation	QPSK (downlink) BPSK (uplink)	QPSK (downlink) BPSK (uplink)
Coherent Detection	User dedicated time multiplexed pilot (downlink and uplink), no common pilot in downlink	Pilot time multiplexed with PC and EIB (uplink) Common continuous pilot channel and auxiliary pilot (downlink)
Channel Multiplexing in Uplink	Control and pilot channel time multiplexed I & Q multiplexing for data and control channel	Control pilot, fundamental and supplemental code multiplexed I & Q multiplexing for data and control channel
Multirate	Variable spreading and multicode	Variable spreading and multicode
Spreading factors	4 – 256 (4.096 Mcps)	4 – 256 (3.6864 Mcps)
Power Control	Open and fast closed	Open and fast closed loop (800

	loop (1.6 KHz)	Hz, higher rates under study)
Spreading (downlink)	Variable length orthogonal sequences for channel separation, Gold sequence for cell and user separation	Variable length Walsh sequences for channel separation, M sequence 2^{15} (same sequence with time shift utilized in different sequence in I & Q channel)
Spreading (uplink)	Variable length orthogonal sequences for channel separation, Gold sequence 2^{41} for user separation (different time shifts in I and Q channel, cycle 2^{16} 10 ms radio frames)	Variable length orthogonal sequences for channel separation, M sequence 2^{15} (same for all users different sequences in I & Q channels), M sequence $2^{41} - 1$ for user separation (different time shifts for different users)
Handover	Soft handover Interfrequency handover	Soft handover Interfrequency handover

Table 1-1 Parameters of WCDMA and cdma2000

TTA I and TTA II are the two wideband CDMA systems that are considered in Korea. The Electronics and Telecommunications Research Institute (ETRI) has established a consortium to define the Korean proposal for IMT-2000. The TTA II concept is closer to cdma2000 and TTA I resembles WCDMA.

Differences Between TTA I and cdma2000

- A 1.6KHz power control rate instead of 800Hz.
- A 10ms frame length instead of a 20ms
- Orthogonal complex Quadrature Phase Shift Keying (QPSK) in the uplink
- Selectable forward error correction code
- The lowest chip rate of 0.9216Mc/s instead of 1.2288Mc/s
- Intercell asynchronous mode

- Quasi-orthogonal code spreading to increase the number of orthogonal codes for packet operation

Differences Between TTA II and WCDMA

- Continuous pilot in the uplink
- QPSK spreading in the downlink
- Orthogonal complex QPSK in the uplink
- Selectable forward error correction code
- Quasi-orthogonal code to reduce the intracell interference
- The downlink pilot structure
- Optional synchronization in the uplink

2.5 Summary

This chapter reviews the CDMA based present and future systems namely, IS-95 and IMT-2000, respectively. An overview of the main wideband CDMA systems is presented by comparing the parameters of WCDMA in Europe and Japan, cdma2000 in the United States and Korean wideband CDMA schemes.

CHAPTER 3

Power Control in CDMA Cellular Networks

3.1 Introduction

In a wireless communication system, mobile users adapt to the time varying radio channel by regulating their transmitter powers. The main aim of power control is to assign users with transmitter power levels so as to minimize the interference users create to each other while meeting certain Quality of Service (QoS) objectives, which are typically defined in terms of the Signal-to-Interference Ratio (SIR).

3.2 Power Control System Model

In this section, we describe the power control system model that is extensively used in the literature. We consider a single cell CDMA radio system. To each communication link, a pair of orthogonal channels from mobile-to-base (uplink) and base-to-mobile (downlink) communication is allocated. Since there is no interference between the uplink and downlink channels, power control for the uplink channel is considered. However, the results can be applied to the downlink as well.

Let $P_i(n)$ be the power transmitted by mobile '*i*' at time instant '*n*'. Typically, the received signal power level, at the base station, depends on the distance between the receiver (base station) and transmitter (mobile station) and effects from the environment. The latter comes about due to wave propagation effects, such as diffraction and reflection phenomenon. Hence, a more relevant model is associated with the channel with a time varying multiplicative power gain, called the link gain. The link gain from mobile '*i*' to base station at time '*n*' is denoted by $G_i(n)$. The gain matrix $\mathbf{G} = \{G_i\}$ is known as the uplink gain matrix. Let η_o be the receiver noise at the base station. The effect of adjacent channel interference is ignored.

Thus, in a cell consisting of a total number of '*I*' mobiles, the Signal-to-Interference ratio (SIR), Γ_i ***as measured at the base station*** for mobile '*i*', at time instant '*n*' can be given as:

$$\Gamma_i(n) = \frac{P_i(n)G_i(n)}{\sum_{l \neq i}^{I} P_l(n)G_l(n) + \eta_o} \qquad \textbf{(3-1)}$$

The time instant '*n*' will from now on be considered as time instants when the base station updates the power of the mobile stations.

3.3 Types of Power Control

Power Control is performed on both the uplink and downlink channels of a CDMA system. Downlink power control is employed to combat the *corner effect*, which occurs when a mobile is situated in a cell corner, and is equidistant from three base stations (assuming a hexagonal cellular structure). In such cases, downlink power control is applied to increase the base stations transmitter power for those mobiles that suffer from excessive intercell interference. It combats the corner effect quite efficiently although it does not change the area-average Bit Error Rate (BER) probability [Stüber & Kchao, 1992].

In the uplink of a CDMA system, the requirement of power control is essential because of multiple access interference. Mobiles in a CDMA system simultaneously transmit messages using the same bandwidth and therefore interfere with one another. Due to propagation mechanisms, the signal received at a base station from a user terminal close to the base station will be stronger than that from another terminal located further away from the base station. The strong signal from the mobile close to the base station then overwhelms the presence of the weaker signal from the mobile far away from the base station. This is called the *near-far* effect. To achieve considerable capacity, all signals, irrespective of distance, should arrive at the base station with the same mean power. Uplink power control attempts to achieve a constant received mean power for each user. The different types of power control algorithms are:

- Open Loop Power Control
- Closed Loop Power Control
- Centralized Power Control
- Distributed Power Control

3.3.1 Open Loop Power Control

Open loop power control has two main functions: it adjusts the initial access channel transmission power of the mobile station and compensates for large abrupt variations in the path loss attenuation. In open loop power control, the mobile station determines an estimate of the propagation loss on the forward link by measuring the received signal strength at the mobile receiver. This gives a rough estimate of the propagation loss for the user on the forward link. The smaller the received power, the larger is the propagation loss and vice-versa. Assuming similar fading characteristics on the forward and reverse link, the mobile station then adjusts its transmit power accordingly.

3.3.2 Closed Loop Power Control

In the IS-95, the uplink and downlink channels have a frequency separation of 20 MHz and their fading processes (fast fading or Rayleigh fading) are therefore not strongly correlated. Even though the average power is approximately the same, the short-term power is different and open loop power control cannot compensate for the uplink fading. To account for the independence of the Rayleigh fading in the uplink and downlink, the base station also controls the mobile station transmit power. In the IS-95, the base station measures the received SIR on the reverse link over a 1.25 ms period, compares it to some target SIR, and decides whether the mobile station transmit power needs to be increased or decreased. It then transmits the power control bits to the mobile on the downlink fundamental code channel every 1.25 ms by puncturing the data symbols. The mobile station extracts the power control bits commands and adjusts its transmit power accordingly. The power adjustment step is a system parameter and is generally set to 0.25, 0.5, or 1.0 dB.

3.3.3 Distributed Power Control

In Distributed power control, the transmitter power levels of the users are updated iteratively so that the power vector converges to the minimum where all the users satisfy their SIR based QoS requirements. The algorithm is distributed in the sense that the users need only to know parameters that can be measured locally such as their channel gains and interference.

3.3.4 Centralized Power Control

In Centralized power control, coordination among all the base stations present in the network is required. Though, it gives better performance than the Distributed power control, this alternative centrally orchestrated power control involves added infrastructure, latency and network vulnerability. Maintenance of a large network also becomes infeasible.

3.4 Framework Model for Power Control

An attempt to set up a framework model for power control is made. Dominant factors and channel quality criteria are identified and several measurable control data is presented.

3.4.1 Dominant factors

A good power control framework should clearly imbed the dominating factors, which cause the interference. We classify them into six categories.

The most dominant factor is the tightly coupled pair of *signaling and modulation scheme* combined with the *multiple access method.* In a non-orthogonal asynchronous uplinks CDMA channel each user interferes with one another. A large number of interferers' results in Gaussian statistics, especially when the overall interference power is practically fixed and is accumulated by interference powers that are assumed to be equal

A second factor is *link orientation,* that is, whether the link is a downlink or an uplink. Signal propagation in both cases could be quite different, especially in wide areas where Radio Access Ports (RAP) antennas are stationary and are placed at elevated locations. User transceivers on the other hand, are usually located amidst buildings and other obstacles, which create shadowing and multipath reflections. Moreover, there are many users who move around and transmit on the uplink; and relatively fewer stationary RAPs, which transmit on the downlink. Such asymmetry is translated into quite different cochannel interference phenomena. Another important differentiator is the transmission and processing capability each end can employ.

A third factor is *environment morphology and topology*. Radio signals propagation strongly depends on landscape and obstacle substance and shape. Therefore, wide areas, urban areas and indoor areas require different interference models. Wide areas may further vary depending on their morphology. Enforced concrete obstacles govern interference in urban arrears with sharp corners making the line-of-sight a dominant factor. Indoor interference is mainly governed by slow walking man-made shadowing and plaster walls.

A fourth factor is the *speed of mobile terminals.* Speed along with the carrier frequency governs the time correlation of the multipath fading. Its statistical distribution is determined by the environment topology, e.g., in wideareas it could be Rayleigh and in urban areas it could be Rician.

A fifth factor is *cell hierarchy*, which has been incorporated into cell planning for better spectrum utilization. Hierarchical cells consist of a very large number of pico cells covered by a smaller number of micro cells. The entire service area could further be covered by macro cells. Mobile users may switch from pico to micro and macro cells depending on their speed, location and connection quality. Their transmission within each cell type is constrained by different power limits and dynamic ranges. Such hierarchical architecture clearly introduces a highly asymmetric interference pattern, which translates itself into yet another statistical model.

The sixth and last factor is the *connection type*, which is closely related to the multiple access method. It can be Continuous Transmission (CTX), Discontinuous Transmission (DTX), packet-switched connection, etc. Interference statistics and time dependency under each connection type are different. In DTX for instance, transmission is ceased when idle speech intervals are detected, making interference more random and less correlated in time. A similar effect with an even stronger impact occurs in packet-switched connections.

3.4.2 Channel quality and objective criteria

The most common criterion of channel quality is its BER, i.e. the average number of erroneous bits/sec. The quality of a voice and other real time connections is also affected by the bit delay variation.

Another quality criterion, which is highly correlated with the BER, is the SIR. SIR-based power control is used more often in modeling because the SIR values are more tractable than BER.

3.4.3 Measurable information

The information which power control utilizes depends on the existing system architecture to which it applies. Practically, a power control algorithm must be distributed and use only local information. Measurements are gathered at a rate, which suits the power control rate. Fast power control, which combats Rayleigh fading, refreshes its information much faster than slow power control, which combats shadow fading. As the transmitter power is controlled, receiver measurements are delayed by a time period, which depends on the propagation delay. Measurements gathered at the receiver are channel gains from the transmitter, total received signal power, received data bits, number of erroneous bits and background receiver noise. Measurements available at the transmitter are its transmission power, its transmitted data bits and gains of the channel from the receiver.

3.5 Aspects of Power Control

On assuming that appropriate base stations are assigned and connections established, the problem of updating the output powers of the transmitters is approached by following the standard block diagram if the signals are interpreted as in Figure 3-1, with respect to mobile i.

- The external disturbances a compromise the power gain G_i and the interference I_i (including the thermal noise η_i)
- The control signal b is the power level P_i
- The measurements available to the controller are represented by y. Normally they consist of a quality related and/or a received signal strength related measure.

- Finally, z represents an adequate quality measure. Reliable measurements are most likely not available on a short time frame.

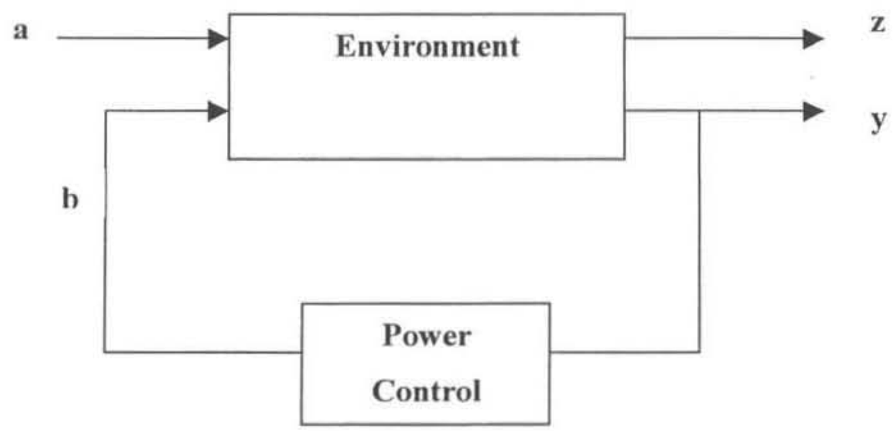

Figure 3-1 The power control problem formulation

The objective is to assign power levels so that z meets the quality specifications $z = z^{t}$ with respect to the adequate quality measure. Additionally, it is desirable to provide sufficient quality to as many users as possible, in order to maximize the capacity of the network.

The following aspects are found to be of interests when characterizing the necessary power control algorithms:

- **Capacity and System load.** Only a limited number of mobile stations can be accommodated in a communication system. It is thus, relevant to describe the system load in a particular situation and also to relate it to the maximal capacity of the network.

- **Centralized/Decentralized Power Controller.** A centralized power controller has all information about the established connections and power gains at hand, and controls all the power levels in the network. A decentralized (distributed) power controller only controls the power of a single transmitter and the algorithm relies on the local information. Practically, decentralized power controllers are more desirable, since a centralized power controller requires extensive control signaling in the network and will suffer from additional time delays.

The distinction is primarily between the types of information used when computing the output powers. Even if an algorithm is considered to be decentralized, it is not necessarily physically located in the mobile station. Instead, the power levels may be computed in the base stations and distributed to the corresponding transmitters. This master-slave relationship facilitates software updates and support.

- **Global Stability and Performance.** Interconnecting several distributed power control algorithms affect properties of the overall global system, such as stability and performance. A relationship between local and global performance has to be established.

- **Quality Measure.** Speech quality is a very subjective quality, and relevant quality measures are different from measures applicable to data traffic. Therefore, the appropriate quality measure is service dependent.

- **Feedback measure.** Feedback can be categorized as *information feedback* or *decision feedback*. Real values are assumed to be available in an information feedback, whereas, in decision feedback a decision based on the measured values is fed back (for an example, whether a measured value is above or below a threshold). In TDMA systems of the second generation, the feedback is provided in measurement reports comprising a *Quality Indicator* (QI), reflecting the quality and a *Received Signal Strength Indicator* (RSSI), reflecting the received signal strength at the receiver. These values are coarsely quantized in order to use few bits. Thus an important question is to determine which quantities can and should be estimated given the available measurements.

- **Constraints.** The output power levels are limited to a given set of values due to hardware constraints. This includes quantizing and the fact that the output power has an upper and a lower limit. Additionally, the various standards include different other constraints.

- **Time Delays.** Measuring and control signaling takes time, which results in time delays in the network. These are primarily of two kinds. Firstly it takes some time to measure and report the measurements to the algorithm. Secondly we have a time delay due to the time it takes before the computed power is actually used in the transmitter. In WCDMA [UMTS 30.06, 1997], each slot contains a power control command. The duration of a slot is 1/1500s. The power computed at time instant $(n-1)$ is actually reflected in measurements not earlier than at time instant. This measurement is used to update the power at time instant $(n+1)$.

A power control system is naturally modeled by the cascade power control structure. A generic model is given in Figure 3-2. Relevant information (Γ_i)is extracted from the possibly delayed measurement by the estimating device *D*. An *outer control loop* computes a ***target SIR*** Γ_o, which on the medium time scale corresponds to the Quality of service (QoS) of the user's service. The *inner loop* assigns transmission powers to track the provided target SIR while compensating for disturbances *a*. The update rate of the inner loop is an order of magnitude faster than the outer loop.

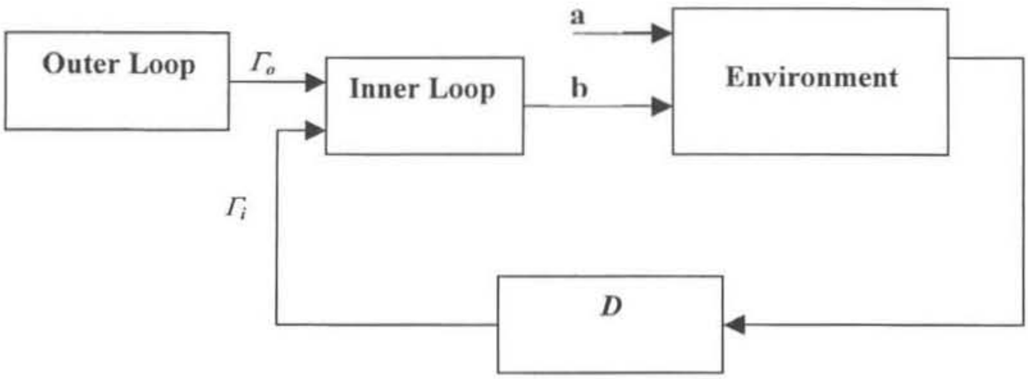

Figure 3-2 Cascade structure of the power controller, where a fast inner loop issues transmission powers to track a target value provided by a slower outer loop, and to compensate for disturbances. Relevant information is extracted from the measurements by the device *D*.

Algorithmic properties are studied at two levels: the *local level* and the *global level*. Capacity, load and whether it is possible to accommodate all users with their data rate requirements (reflected by the SIR targets) are typically considered at the global level. Stability and convergence are also considered at the global level. Conversely on a local level, target SIRs are assumed constant and that it is possible to accommodate all users. It is assumed that the inner power control loops successfully compensates for the fast variations, so that the power gains can be considered as constant. The tracking capabilities are then dealt with in terms of the inner control loop bandwidth and stability.

3.6 Survey of Proposed Power Control Algorithms

Figure 3-3 illustrates the various power control schemes that can be categorised based on their types and applications in a cellular CDMA network. The ambition is not to provide a complete coverage of the area, but rather to outline some important and central contributions.

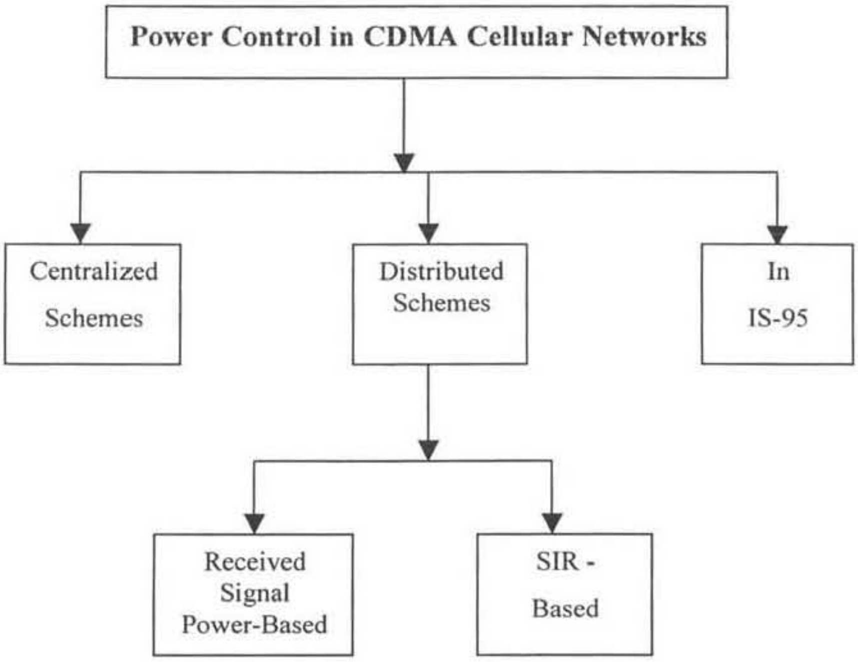

Figure 3-3 Power Control Schemes in CDMA Cellular Networks

3.6.1 Centralized Power Control Algorithms

If the central controller (or the base station) has knowledge of all the Signal-to-Interference ratio (SIR) of the mobiles as well as the power it receives from each mobile, then the transmission powers of every transmitter can be computed in a centralized fashion.

Early work on centralized power control algorithms based on SIR presented that for a given link, adjusting the powers such that all the admitted connections operate at the same SIR can maximize the capacity requirement. This concept is referred to as *SIR balancing* for power control. The proposed power control algorithm called the 'optimum power control algorithm' was based on solving a problem on an eigenvalue of link gain matrix. The solution is optimal in the sense that the minimum SIR of all the communication links is maximized [Zander, 1992a], [Grandhi *et al.*, 1993] and there exists no other power vector yielding higher SIR Γ_o for all receivers. Zander [1992a] defined the global optimum power control algorithm, as an algorithm that in every moment has access to the entire link gain matrix **G** and may instantaneously control the entire transmitter power vector **P**. The scheme shows that optimum power vector **P** has the following form:

$$P_i(n) \begin{cases} = 0 & \text{if } \Gamma_i(n) < \Gamma_o \\ \neq 0 & \text{if } \Gamma_i(n) \geq \Gamma_o \end{cases} \tag{3-2}$$

where $\Gamma_i(n)$ is the SIR at the base station for mobile 'i' at time instant 'n' and Γ_o is the constant target SIR. Thus, the scheme shows that Γ_o is achievable if there exists a power vector $\mathbf{P} > 0$ such that $\Gamma_i(n) \geq \Gamma_o$. Since the result is based on an eigenvalue problem, the optimal power vector is relative, so if $\mathbf{P}_i^*$ is an optimal power vector, so is $k\mathbf{P}_i^*$. Thermal noise is not included in the analysis. However, in the noisy case, the influence of the noise can be made arbitrarily small. The global optimum power control algorithm may be used to derive an upper bound on the performance of any local algorithm, as in a local algorithm, each base station (or mobile) controls its own transmitter power based on only a limited knowledge about **G**.

These results hold under the assumption that the receiver can utilize all the desired received signal power $R_i(n)$. If the receiver can only utilize a faction of that power, then the remainder acts as interference, auto-interference. Auto-interference results in a lower optimal balanced SIR [Godlewski & Nuaymi, 1999].

Practically, a specific *balanced target SIR* at each receiver is desirable. This is relevant if the objective, for example, is to provide speech services of the same quality to all users. A corresponding balancing power vector is determined, which is proven to be feasible only if $\Gamma_i < \Gamma_o$.

In the analyses above, it has been assumed that the transmitters can use any power. However, practically there are constraints on the power levels. In a centralized scheme, upper bounds on the maximum transmitter power can be set [Grandhi, Zander & Yates, 1995].

3.6.2 Distributed (Decentralized) Power Control Algorithms

Transmitted powers of the mobile users can be updated distributedly either on the basis of the received power or the SIR calculated at the base stations.

3.6.2.1 Distributed Power Control Algorithms Based on Received Signal Power

Two schemes can be found in the literature. In the first scheme called the Constant Received Power (CRP) algorithm, channel inversion is the main objective [Anderlind, 1997].

$$P_i(n+1) = P_i(n)\frac{R'}{R_i(n)} \qquad \textbf{(3-3)}$$

where R^t is the target signal received power and $R_i(n) = P_i(n) * G_i(n)$ is the actual received signal power. $P_i(n)$ and $G_i(n)$ are the transmitted power and link gain of mobile '*i*' as calculated at time '*n*'.

In the second scheme, the transmitted powers of the mobile stations are controlled so that the powers received at the connected base station are all the same. The transmitted power can be given as [Adachi, 1997], [Ariyavisitakul & Chang, 1993], [Chang & Wang, 1996a], [Chang & Wang, 1996b]:

$$P_i(n+1) = \begin{cases} \beta_i P_i(n) & \text{if} \quad R_i(n) \le R^t \\ \beta_i^{-1} P_i(n) & \text{if} \quad R_i(n) > R^t \end{cases} \tag{3-4}$$

where β_i is the design parameter. Since only one information bit is needed for signaling, the scheme is bandwidth efficient, which enables the use of a high update frequency.

SIR is related to perceived transmission quality. In CDMA cellular systems, not only thermal noise but also interfering signal power from other users limit the performance and capacity. A related problem is therefore to assign appropriate target values R^t for these algorithms to control the interference between cells [Viterbi, 1995].

3.6.2.2 Distributed Power Control Algorithms Based on SIR

Early work based on the distributed power control algorithms laid emphasis on making the centralized power control algorithms to be more computationally efficient. The proposed algorithms were based on results for iterative computations of eigenvectors of the link gain matrix **G**. Similar ideas appeared in the work of Zander [1992b]. Here the Distributed Balancing (DB) algorithm is suggested as:

$$P_i(n+1) = \beta_i P_i(n)\left(1 + \frac{1}{\Gamma_i(n)}\right) \tag{3-5}$$

The DB algorithm is essentially a method for finding the dominant eigenvalue and its corresponding eigenvector in the link gain matrix **G**. If the thermal noise is neglected, the DB algorithm converges to the balancing power vector, which corresponds to Γ_0. Initially the DB algorithm appears to be distributed since it is based on $\Gamma_i(n)$, which is a measurement of the SIR at the receiver. However, it turns out that the choice of the design parameter β_i is problematic, since $P_i(n)$, transmitter power of mobile i, drift towards Zero or infinity, if not appropriately chosen. This choice of β_i can be seen as a normalization procedure and it must be based on global information. Thus, this is not a fully decentralized algorithm.

A slight modification to the DB algorithm is the Distributed Power Control (DPC) algorithm [Grandhi *et al.*, 1994]:

$$P_i(n+1) = \beta_i \frac{P_i(n)}{\Gamma_i(n)} \tag{3-6}$$

When neglecting the thermal noise, the DPC algorithm also converges to optimum power and simulation results indicates that the convergence is faster than when using the DB algorithm [Lee, Lin & Su, 1995]. Nevertheless, the problem of normalizing the powers by cleverly adapting β_i still remain.

Yet another algorithm, similar to those described above, was proposed [Lin, 1995]:

$$P_i(n+1) = \beta_i P_i(n)\left(\frac{1}{\Gamma_i(n)}\right)^{\xi_i} \qquad \textbf{(3-7)}$$

However, this also suffers from the problem of proper choice of parameters β_i and ξ_i. The drawback with these distributed algorithms is that they are not fully decentralized. The normalization procedure requires signaling between the algorithms, which is undesirable in practice.

A different version of the DPC algorithm was proposed by Foschini and Miljanic [1993]. They pointed out that the normalization procedure was unnecessary when taking noise into consideration. Instead β_i was seen as the target SIR, which the algorithm strives towards, if this is feasible i.e., $\beta_i < \Gamma_o$. Hence, the algorithm can be rewritten as:

$$P_i(n+1) = P_i(n)\frac{\Gamma_o}{\Gamma_i(n)} \qquad \textbf{(3-8)}$$

With the DPC algorithm as the base, extensions have been proposed when considering systems with output power constraints called the *Distributed Constrained Power Control* (DCPC) algorithm [Grandhi *et al.*, 1995]. The algorithm can be given as:

$$P_i(n+1) = \min\left(P_{i(\max)}, P_i(n)\frac{\Gamma_o}{\Gamma_i(n)}\right) \qquad \textbf{(3-9)}$$

It addresses systems where the output power is bounded.

In the above-proposed algorithms values in linear scale are utilized. Yates [1995] used values in logarithmic scale as given in the following algorithm:

$$\log P_i(n+1) = \beta_i P_i(n) + (1-\beta_i)x_i(n), \qquad 0 < \beta_i < 1 \tag{3-10}$$

where $x_i(n) = \Gamma_o + P_i(n) - \Gamma_i(n)$ **(3-11)**

Yates proved the convergence of this algorithm to Γ_i (when $\Gamma_i < \Gamma_o$) and introduced the term logarithmic interference averaging to describe the effect of the parameter β_i. Clearly, $\beta_i=1$ corresponds to no power control, while $\beta_i=0$ yields the DPC algorithm described in equation (3-7).

Power control algorithms, which employ decision feedback, can benefit from the low signaling bandwidth, consequently enabling a high update frequency. One such algorithm, which uses decision feedback, is given by:

$$P_i(n+1) = \begin{cases} \beta_i P_i(n) & \text{if} \quad \Gamma_i(n) \le \Gamma_o \\ \beta_i^{-1} P_i(n) & \text{if} \quad \Gamma_i(n) > \Gamma_o \end{cases} \tag{3-12}$$

This algorithm is used for emerging WCDMA system with an update frequency of 1500 Hz [Dahlman, Benning, Knutsson, Ovesjö, Persson & Roobol, 1998], [UMTS 30.06, 1997]. The algorithm is referred to as the Fixed Step Power Control (FSPC) algorithm. This has been extended by [Sung & Wong, 1999a], [Ariyavisitakul & Chang, 1991] to a distributed power control algorithm, which uses fixed step as shown in Figure 3-4 [Sim, Gunawan, Soong & Soh, 1999]. If the received power is below or above the target window, the base station informs the mobile to increase or decrease its power to a next level and this is done by a fixed step at each time. This continues till the required level is achieved. Generally the step size is kept constant at 1dB. Although two bits are needed for each power control command in the fixed-step technique, it is seen that the convergence to the required SIR level takes longer. This algorithm bears some resemblance to the algorithms investigated by Ariyavisitakul [1994a] and Chung & Sollenberger [1994]. The algorithm performs nearly as well as SIR balancing scheme. However, the SIR is kept constant throughout in the system.

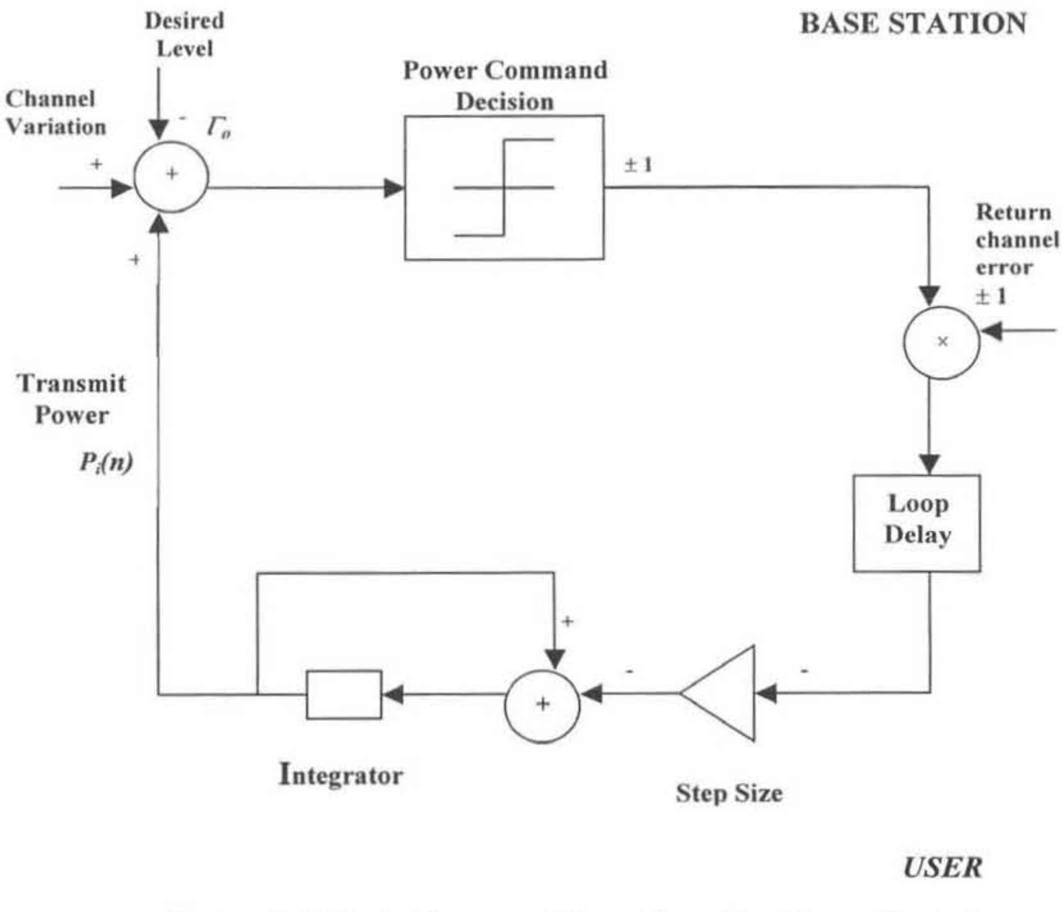

Figure 3-4 Block Diagram of Fixed Step Size Power Control

The results obtained when implementing this Fixed Step Size Power Control algorithm into the network are relevant to our study, as these will be compared to those obtained when our proposed power control algorithm is employed (Chapter 5), for better understanding and performance analysis.

The step size can be adapted as well, normally at a much lower updating frequency than the power control update. Such algorithms are denoted as Adaptive-step power control (ASPC) algorithms.

As with the algorithms based on received signal power, a related problem is to provide a relevant target SIR [Kawai, Suda & Adachi, 1999], [Won, Kim, An & Jeong, 1998]. A crucial problem is to issue a target SIR that corresponds to a feasible power control problem. If the value is set too high, it is not possible to support all the mobiles. Instead the algorithms will start competing to obtain the target SIR. This competition will last until several transmitters are using maximal powers, still without achieving the target SIR at the corresponding receiver. A user with favorable propagation conditions may use a higher power, and vice versa, to counteract this *party-effect*.

More recent work [Jäntti & Kim, 2000] has considered distributed power control schemes that use power levels of both current and previous iterations for power update. The algorithm is developed by applying the successive overrelaxation method to the power control problem. The advantage of such a second-order algorithm is in faster convergence. The constrained second-order power control (CSOPC) algorithm is given as:

$$P_i(n+1) = \min\{P, \{w(n)\Delta_i(n)P_i(n) + (1 - w(n)P_i(n-1)\}\} \qquad \textbf{(3-13)}$$

$$\text{where} \quad \Delta_i(n) = \begin{cases} \Delta & \text{if} \quad \Gamma_i(n) \le \Gamma_o \\ \dfrac{1}{\Delta} & \text{if} \quad \Gamma_i(n) > \Gamma_o \end{cases} \qquad \textbf{(3-14)}$$

$w(n)$ is a non-increasing sequence of control parameter satisfying $1 < w(n) < 2$. $w(1) = w(2) < w(3) = w(4) < \ldots. < w(2n+1) = w(2n) < \ldots.$and $\lim_{n \to \infty} w(n) = 1$. The step size Δ in this proposed algorithm is fixed at 0.5 dB. The scheme significantly enhances the convergence speed of power control. It is also shown that the algorithm has a higher potential for increasing the radio network capacity.

3.6.3 Power Control Algorithms in IS-95

The closed loop power control in IS-95 involves both the base station and the mobile user to compensate for power fluctuations due to fast Rayleigh fading. The base station continuously monitors the reverse link and measures the link quality. If the link quality deteriorates, the base station commands the mobile user, via the forward link, to increase the power. And if the link quality is very good, which indicates that there is excess power in the reverse link, the base station then commands the mobile to decrease the power. Ideally, Frame Error Rate (FER) is a good indicator of link quality. But because it takes longer for the base station to accumulate enough bits to calculate FER, SIR is used as an indicator of reverse link quality.

The reverse link closed loop power control can be summarized as:

- The base station continuously monitors SIR on the reverse link.
- If SIR is very high (i.e., if it exceeds a certain threshold), then the base station commands the mobile to decrease it's transmit power.
- If SIR is very low (i.e., if it drops below a certain threshold), then the base station commands the mobile to increase it's transmit power.

The base station sends the power control commands to the mobile using the forward link. These power control commands are in form of Power Control Bits

(PCBs). The amount of mobile power increase and power decrease per each PCB is normally +1dB or –1dB. The PCBs are continuously transmitted to the mobile by the base station. The rate of PCB transmission is 800bps, a PCB is sent once every 1.25ms. A class of distributed asynchronous power algorithm implemented in IS-95 is presented in [Herdtner & Chong, 2000].

3.7 Summary

This Chapter reviews the relevant existing literature on power control in CDMA networks. Firstly, a general model of power control is described, followed by an explanation of the different types of power control schemes, that can be categorized as: open loop, closed loop, centralized and distributed schemes. A framework model for power control identifying the dominant factors and channel quality criteria is discussed. After presenting the various aspects of power control, a comprehensive survey on the existing power control algorithms is presented which can be categorized depending on the execution location, into centralized power control algorithms and distributed power control algorithms. Finally, the Chapter presents a brief description on the power control implemented in IS-95.

CHAPTER 4

POWER CONTROL IN MULTIMEDIA NETWORKS

4.1 Introduction

As introduced in Chapter 1, third generation systems are required to accommodate various services including speech, images, video, file transfer, interactive data and Internet access. The growing user population of wireless multimedia applications demand new, high capacity, integrated multiple access schemes, to which CDMA has many advantages to offer. To ensure that the maximum achievable capacity of multimedia CDMA systems could be reached and could be efficiently utilized, accurate power control mechanisms should be employed. Many studies on power control performances and its effects on capacity have been done. Most of these studies, dealt with single media communications as covered in the previous chapter. In this Chapter, we discuss the factors influencing QoS in multimedia networks and the structure of power control for multimedia traffic. The main aim of this Chapter is to give a literature survey on the proposed power control algorithms in multimedia networks.

4.2 Factors Influencing QoS in Multimedia Networks

Quality of Service (QoS) is a measure of the satisfaction experienced by a person using a product or service. In a wireless communication system, there are several ways to formulate the QoS objectives quantitatively. The common QoS criteria are: acceptable Signal-to-Interference ratio (SIR), maximum acceptable probability of error (BER), maximum acceptable delay, minimum acceptable data transmission rate and maximum acceptable power consumption.

The SIR and BER criteria are directly related. For low probabilities of error a system is considered to be unacceptable (QoS is equal to zero) when the SIR is below a target level, whereas if the SIR is greater than or equal to the target level, the QoS is assumed to be acceptable. Most power control algorithms, implicitly assume that there is no benefit to having an SIR above the target level. Examples of acceptable SIR are 7dB in Global System for Mobile Communications (GSM) digital systems carrying voice, and 6dB in CDMA system [Goodman, 1997].

In a data system, the SIR directly influences both delay and low probability of error. When a system contains Forward Error Correction (FEC) coding, a transmission error is considered to be an error that appears at the output of the FEC decoder. Because data systems are intolerant to errors, they deploy powerful error detecting schemes. When a transmission error is detected, the system retransmits the affected data. A high SIR, thus increases the system throughput, and decreases the delay relative to a system with a low SIR.

In addition to the speed of data transfer, power consumption is an important factor in mobile computing. The satisfaction experienced by someone using a portable device depends on how often one has to replace or recharge the batteries in the device. Thus, it can be seen that *QoS depends on both SIR and transmitted power*. These quantities are strongly interdependent. With everything unchanged, SIR is directly proportional to transmitted power. In cellular CDMA system, however, many transmissions interfere with one another, and an increase in the power of one transmitter reduces the SIR of many other signals.

4.3 Multimedia Traffic Characteristics

Various services that can be used by a mobile in a multimedia network can be classified according to their traffic characteristics. This section describes these classes of service and also provides power control structure, which is required to regulate and update the transmit power levels in each of these classes of service.

4.3.1 Service Class I

This class includes services, such as *speech* and *video*, which show symmetric traffic characteristics. For Service Class I, the communication link between a user and a base station is symmetrically established. Almost the same amounts of information are exchanged between a mobile station and a base station.

For this service class, power control channel is imbedded into the downlink traffic channel. Thus, when the signal of a mobile station arrives at base station processor and the signal level is extracted, a power control command is generated. This command is delivered to the mobile station immediately on the downlink power control channel. This structure can minimize the delay and track the channel variations quickly. Since, uplink and downlink channels are simultaneously connected during a call connection period, the power control channel can be established at the call set-up phase.

4.3.2 Service Class II

This class includes services, which exhibit asymmetric traffic characteristics, such as *file transfer, images,* and *facsimiles*. The downlink holding time for these services is rather short. On the contrary, the uplink holding time is far longer.

For this service class, common power control signaling channels are available to all users. Power control commands for connected users of service class II are multiplexed on the downlink dedicated power control channels. These channels may make the base stations more complex and increase the signaling traffic. If no power control scheme is applied, the uplink channel capacity can be significantly decreased and the appropriate link quality cannot be maintained. Therefore, it is desirable that dedicated power control channel should be allocated at the call set-up phase.

4.3.3 Service Class III

This class includes services, such as *email, interactive data* and *Internet access*. The uplink channel holding time is rather short. There is no need to negotiate with the base station with respect to call connections because these services might not significantly affect the uplink quality. A mobile station can access the uplink channel at any time except when the uplink channel is in a serious congestion.

For this service class, no explicit power control channel is allocated on the initial access. The mobile stations or mobile users first estimate the propagation loss from the base station. From this value, they estimate the appropriate power levels for their data packets. Generally, the data packet length for service class III is short and transmission rate is rather low. Therefore, interference contributions to the radio channels are insignificant. Simple but effective power control can be performed through the estimation of the channel attenuations.

4.4 Survey of Proposed Power Control Schemes in Multimedia Networks

Figure 4-1, illustrates the different power control schemes that have been published in the literature.

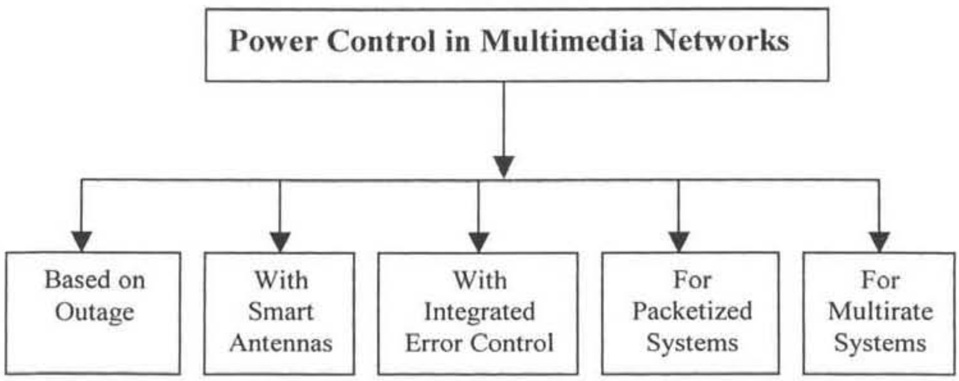

Figure 4-1 Power Control Schemes in Multimedia Networks

4.4.1 Power Control Based on Outage Constraint in Multimedia CDMA System

Su, Annamalai & Lu [1999] presented a method to optimize the power allocation in the reverse link for an integrated network with multiple traffic types. The optimization problem is formulated as:

$$\text{minimize} \sum_{j=1}^{J}\sum_{i=1}^{I} P_{ij}(n)$$

$$\text{subject to } \frac{t_j - I_{ij}(n)}{\sqrt{2V_{ij}(n)}} \geq \phi_j \qquad \textbf{(4-1)}$$

where J is the number of traffic types supported by the system, $\phi_j = erfc^{-1}(2\ P_{out,\ j})$ and subscript j denotes the traffic type. $P_{ij}(n)$ is the transmit power of mobile 'i' of class 'j' at time 'n' and t_j the outage threshold. $I_{ij}(n)$ and $V_{ij}(n)$ denote the mean and the variance of the total multiuser interference to reference user 'i' of the j^{th} type at time 'n'.

Whether or not a traffic composition denoting the number of calls for each service class, is admissible can be determined by numerically solving the nonlinear equations representing the service requirements. This is efficiently accomplished with the aid of a *logarithmic barrier-function optimizer*. Constrained optimization problem of minimizing $f(x) = c^T x$, subject to $x \geq 0$ is reduced to:

$$\text{minimize } f_\mu(x) = c^T x - \mu \sum_{j=1}^{J}\sum_{i=1}^{I} \ln x_{ij} \qquad \textbf{(4-2)}$$

where T is the throughput and μ is a strictly positive scalar known as *barrier parameter*. When the barrier term is heavily weighted, a minimizer of the composite function will lie far away from the boundary of the cell. By applying the above basic idea of the logarithmic barrier algorithm in both perfect power control and imperfect power control scenario, the optimal power assignment strategy for a CDMA system with a number of distinct services is obtained.

The scheme handles dissimilar outage requirements for different services as well as the imperfect power control cases. The scheme also provides a guideline for setting the maximum transmit power levels for each of the distinct service classes so that the network throughput is maximized for a specified fixed total transmit power [Sampath, Kumar & Holtzman, 1995].

Kanade & Guo [1999] proposed a slightly different scheme. It incorporates different performance requirements for different services. The radio capacity or overall throughput of a CDMA cellular system with multiple traffic types can be increased significantly by assigning suitable power levels to different traffic types. The outage probability of user '*i*' of service class '*j*' is expressed as:

$$P_{ij,out} = \int_0^{\infty} \frac{1}{2} f(w)\, erfc\left(\frac{\dfrac{w\, G_{ij}(n) P_{ij}(n)}{(E_b / N_o)_j} - \eta_o^2 - I_{ij}(n)}{\sqrt{2 V_{ij}(n)}} \right) dw \qquad \textbf{(4-3)}$$

where $f(w)$ is the lognormal power density function (PDF) of the received power from user '*i*'. $G_{ij}(n)$ and $P_{ij}(n)$ are link gain and power transmitted by mobile '*i*' of class '*j*' at time '*n*', respectively. $I_{ij}(n)$ and $V_{ij}(n)$ are the mean and variance of the total interference to the reference user '*i*' of class '*j*' at time '*n*'. η_o is the background noise power, while $(E_b / N_o)_j$ (ratio of signal energy per bit to noise) is the QoS requirement for each service class '*j*'. Thus, in this scheme, transmit powers $P_{ij}(n)$ are mainly determined by the QoS requirements for different traffic types and chosen such that $P_{ij,out}$ is minimum.

4.4.2 Power Control with Smart Antennas in Multimedia Networks

Automatic power control and smart antennas can be used to allocate and control the levels of SIR according to the individual need of each user and the quality of channels that the mobile system can allow, given the interference present at any given time [Mercado & Liu, 2000]. Each service type is assigned a target SIR level, and it endeavours to choose the transmission power assignments and receiver antenna weights that take the receiver SIR levels as close as possible to those target levels. Two problems are addressed: firstly, how to accommodate the SIR requirements for each user given its desired multimedia service type, and secondly, how to swiftly adopt and adapt users to the system. The latter point arises when the system is initiating service for a new user, whether the new user is initiating a call or if it is handing off from another base station. During the process, the system calculates the power vector for all co-channel mobile users, and the antenna weights for all the associated base stations. These values are obtained through iterative algorithms that require certain constraints for convergence. Practically, an extensive delay before activating the new user is not allowed. This reduces the activation latency for new multimedia users.

The Signal-to-Interference ratio (SIR) for user 'i' of class 'j' at time 'n' is given as:

$$\Gamma_{ij}(n) = \frac{G_{ij}(n)P_{ij}(n)}{\sum_{j=1}^{J}\sum_{i=1}^{I} G_{ij}(n)\left|\mathbf{w}_{ij}^{H}\mathbf{a}_{ij}\right|^{2} P_{ij}(n) + n_{ij}} \qquad \textbf{(4-4)}$$

where $\mathbf{a}_{ij}$ is the array response of the base station array to mobile source, $\mathbf{w}_{ij}$ contains the weight applied to the inputs to the antenna elements of base station. $\mathbf{w}_{ij}^{H}$ is the Hermitian conjugate of the vector $\mathbf{w}_{ij}$, $G_{ij}(n)$ and $P_{ij}(n)$ are the link gain and transmit power at time 'n' respectively, and $n_{ij} = \mathbf{w}_{ij}^{H}\, \mathbf{N}_{ij}\, \mathbf{w}_{ij}$ where $\mathbf{N}_{ij}$ is the vector matrix of thermal noise at the antenna elements at the base station receiver. The problem statement for the power control is given as:

minimize $\sum_{j=1}^{J}\sum_{i=1}^{M} P_{ij}$

subject to $(I - \mathbf{\Gamma F})\mathbf{P} \geq \mathbf{u}$ **(4-5)**

$$\text{where } \mathbf{F} = \begin{pmatrix} 0 & \frac{G_{12}\left|\mathbf{w}_1^H \mathbf{a}_{12}\right|^2}{G_{11}} & . \; . & \frac{G_{1M}\left|\mathbf{w}_1^M \mathbf{a}_{12}\right|^2}{G_{11}} \\ \frac{G_{21}\left|\mathbf{w}_2^H \mathbf{a}_{21}\right|^2}{G_{22}} & 0 & . \; . & \frac{G_{2M}\left|\mathbf{w}_2^H \mathbf{a}_{2M}\right|^2}{G_{22}} \\ . & . & . \; . & . \\ . & . & . \; . & . \\ \frac{G_{M1}\left|\mathbf{w}_M^H \mathbf{a}_{M1}\right|^2}{G_{MM}} & \frac{G_{M2}\left|\mathbf{w}_M^H \mathbf{a}_{M2}\right|}{G_{MM}} & . \; . & 0 \end{pmatrix} \quad \textbf{(4-6)}$$

$$\mathbf{\Gamma} = \text{diag}\,(\Gamma_1 \,..........\, \Gamma_J) \quad \textbf{(4-7)}$$

and $$\mathbf{u} = \left(\Gamma_1 \frac{n_1}{G_{11}} \; \Gamma_2 \frac{n_2}{G_{22}} \; .... \; \Gamma_J \frac{n_J}{G_{JJ}}\right)^T \quad \textbf{(4-8)}$$

P is the power vector for all the cochannel mobile stations. The optimum power vector is given as:

$$\hat{\mathbf{P}} = (I - \mathbf{\Gamma F})^{-1}\mathbf{u} \quad \textbf{(4-9)}$$

An optimal solution is obtained if there exists a feasible set of weight vectors $\{\mathbf{w}_i\}_{i=1,2......I}$ in the complex plane such that $\rho(\mathbf{\Gamma F}) < 1$ (ρ is an eigenvalue of $\mathbf{\Gamma F}$).

4.4.3 Power Control with Integrated Error Control in Multimedia CDMA System

Power control has also been studied as part of the optimization problem for system resource allocation [Yun & Messerschmitt, 1995], [Hanly, 1995], [Soleimanipour, Zhuang & Freeman, 1998]. In the previous work on power control for multimedia communications, emphasis has been laid either on the power control techniques to achieve a given required E_b/I_o (ratio of signal energy per bit to interference) at the receiver for each traffic type, or on optimal system resource management under the assumption that the required E_b/I_o is given. To the best of our knowledge, no work is available in the open literature on defining the optimal received E_b/I_o value given the required transmission rate and the user traffic type.

Zhuang [1999] considers the transmission error control and power control for the non-coherent reverse link transmission when convolutional coding with automatic retransmission request (ARQ) and without ARQ is used for error sensitive traffic and delay sensitive traffic, respectively. A strategy for integrating the transmission error control techniques with power control is presented, which maximizes the frequency spectrum efficiency and, at the same time, guarantees various QoS requirements. Using a different approach on power control for multimedia communications, it focuses on defining the optimum received E_b/I_o value based on required transmission BER and the traffic type.

Let $\widetilde{R}_{ij}$ denote the average received power required to achieve a BER of value $\widetilde{p}_b$, which is larger than the required BER (p_b). The probability bit error $\widetilde{p}_b$ is to be further reduced to p_b by retransmission. If R_{ij} denotes the statistical average of the received power from mobile 'i' of class 'j', which takes retransmission into consideration, then the value of R_{ij} needed to achieve a required BER p_b is:

$$R_{ij} = \frac{\widetilde{R}_{ij}}{1 - p_R} \tag{4-10}$$

where p_R is the probability of data retransmission. The main aim of this scheme is to determine the received power level $\widetilde{R}_{ij}$ (and hence E_b/I_o value) in such a way that the total received power R_{ij} is minimized. In other words, based on channel coding scheme used and the required BER (p_b), $\widetilde{p}_b$ is determined which results in a minimal R_{ij}, and power control strives to achieve the target E_b/I_o value corresponding to $\widetilde{p}_b$ for the channel-coding scheme. In this way, error control is integrated with power control to achieve the required BER and minimal interference level that the mobile introduces to all other users, leading to a maximal utilization of the radio frequency spectrum.

4.4.4 Power Control for Packetized Multiservice CDMA System

A packetized DS-CDMA network model that supports voice, data and video traffic in a protocol compatible with ATM is proposed in [Manji & Zhuang, 2000]. The system supports CBR voice, VBR data and VBR video traffic. Convolutional coding is used for voice packet, Bose-Chaudhuri-Hocquenghem (BCH) coding for data (with an ARQ protocol) and video packets. Power control is implemented on the reverse link, which combines channel estimation with closed-loop power control. The proposed power control scheme is performed by comparing the received signal power $R_{ij}(n)$ from mobile '*i*' of class '*j*' at the base station, with a predefined threshold d_t over several symbols in order to generate a power control command at time '*n*'. The threshold d_t for each user is determined by its BER requirement because the SIR of the received signal can be directly mapped to a corresponding BER. The control algorithm sends a 2-bit power command for delay sensitive traffic, as a feedback. The first bit is the output of a comparator with the inputs $R_{ij}(n)$ and d_t, and the second bit with inputs $R_{ij}(n)$ and d_1 or d_2 depending on the first bit where $d_i < d_t < d_2$. Thus, the power adjustments are:

if $R_{ij}(n) < d_1$, then increase transmitted power by $l_1\Delta$
if $d_1 \leq R_{ij}(n) \leq d_t$, then increase transmitted power by Δ
if $d_t \leq R_{ij}(n) \leq d_2$, then decrease transmitted power by Δ
if $d_2 < R_{ij}(n)$, then decrease transmitted power by $l_2\Delta$

where d_1, d_2, l_1 and l_2 are design parameters. In the context of the overall performance, it is better to decrease the transmitted power for one user whose received power is above the threshold than to increase the power for user below the threshold. As a result, $l_1 \leq l_2$. Using $l_1 = l_2 = 1$ is equivalent to using a 1-bit power command. For delay insensitive traffic, only the first bit is used for a 1-bit power command. The scheme shows that the power control error does not increase the delay between the end of transmission of one packet and the beginning of the next packet. Therefore, it is suitable for packetized transmission and busty data traffic.

4.4.5 Power Control for Multirate Multimedia CDMA System

There are many ways to design a DS-CDMA system to support multirate services [Yao & Geraniotis, 1996], [Ottosson & Svensson, 1995]. One way to do so is to spread signals independent of the bit rate, to the same bandwidth. This is done by keeping the chip rate constant. Users transmitting at low bit rate thus have a high processing gain. This allows those users to transmit at a lower power. Therefore, the conventional constant received power scheme is not appropriate in such a multirate system. A more sophisticated power control scheme is needed to achieve diverse QoS and rate requirement. Schemes based on the equal signal strength rule and the equal error probability rules are used in [Wu & Geraniotis, 1995].

Data terminals require a very different objective function than the voice terminals. To handle this situation, the terminals can be divided into delay-tolerable and delay-sensitive [Sung & Wong, 1999b]. For delay-tolerable terminals, the problem is formulated as a constrained optimization problem. The objective is to maximize the total effective rate. When the bandwidth is large, the power control rule takes a very simple form. In the proposed scheme, it is assumed that the received power is normalized to an appropriate constant R_T. The value of R_T depends on the total number of users I in service classes J, the maximum power constraint of each user and the receiver noise η_o. R_T is determined in order to maximize the data rate T, subject to the constraint:

$$\sum_{j=1}^{J}\sum_{i=1}^{I} R_{ij}(n) = R_T \qquad \textbf{(4-11)}$$

where $R_{ij}(n) = G_{ij}(n) * P_{ij}(n)$, is the power received at the base station from user 'i' of class 'j' at time 'n'.

To tackle the problem, the following coordinate transformation is employed:

$$\frac{1}{1+\Gamma_{ij}(n)} = 1 - \frac{R_{ij}(n)}{R_T + \eta_o} \qquad \textbf{(4-12)}$$

There is a one-to-one mapping between nonnegative SIR $\Gamma_{ij}(n)$. Total received power assumption, hence, translates into:

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\frac{1}{1+\Gamma_{ij}(n)}=1-\frac{R_T}{R_T+\eta_o} \tag{4-13}$$

The SIR target of each mobile terminal is set proportional to its transmission rate. The proportionality constant depends on the value of R_T. At any particular instant of time '*n*', received SIR $\Gamma_{ij}(n)$ is directly proportional to the data rate for all mobile '*i*' users of class '*j*'. The rule can easily be put into practice.

For a multimedia system, which also contains delay-sensitive terminals, the nature of the problem remains unchanged. The SIR of delay sensitive terminals (class $j = 2$) is given as:

$$\Gamma_{i2}(n)=\frac{R_{i2}(n)}{\sum_{m\neq i}^{I}R_{m2}(n)+R_{T1}+\eta_o} \tag{4-14}$$

The optimal power of class 2 is derived and determined as [Sung & Wong, 1999b]:

$$\Gamma_{i2}(n)=\frac{R_{i2}(n)}{\sum_{m\neq i}^{I}R_{m2}(n)+\frac{L_{i2}\,R_{T1}+\eta_o}{1-L_{i2}}} \tag{4-15}$$

where L_{i2} is the traffic load of class 2 which can be calculated as:

$$L_{i2}=\frac{\Gamma_{o2}}{\Gamma_{o2}+1} \tag{4-16}$$

where Γ_{o2} is the constant SIR target for mobiles of the delay sensitive users.

4.5 Summary

This Chapter reviews the relevant existing literature on power control in multimedia CDMA networks. Factors influencing QoS in multimedia network is presented. The Chapter describes various classes of service, categorised according to their traffic characteristics in a multimedia system. Power control structures for these classes of service are also discussed. Finally, the Chapter gives a comprehensive survey of the existing power control algorithms in multimedia networks.

CHAPTER 5

DISTRIBUTED VARIABLE STEP SIZE POWER CONTROL ALGORITHM IN CELLULAR CDMA SYSTEM WITH HETEROGENEOUS TRAFFIC TYPES

5.1 Introduction

In this chapter, a distributed power control scheme for the next-generation multi-service cellular CDMA systems is presented. It is known that in cellular systems, a mobile user may adjust its transmitter power so as to achieve satisfactory QoS, which depends on SIR. Since power is a valuable commodity for the users, a mobile user prefers to use less power to obtain better QoS from assigned base stations. Consequently, it is observed that on one hand, for a given SIR, a mobile user prefers to transmit less power. On the other hand, for a fixed transmitted power, a user prefers better SIR.

In the proposed Distributed Power Control Algorithm, the transmitted power of the mobiles in each of the service classes is to be updated. The received power and the SIR for each of the service classes are adapted locally (by variable power level increments/decrements) based on the measurements of the mean and the variance of the interference caused by all the other active mobiles. The SIR values are tailored to provide different QoS degrees in the cellular CDMA systems.

5.2 Fading-Loss Model

The signal received at a base station is assumed to undergo three kinds of losses: path loss, lognormal shadow fading and fast fading. These losses are assumed to be independent. The main objective of the loss models is to study the power gain at the base station receiver. To that end, what is relevant as far as these losses are concerned is the rate at which they occur as well as the fading levels that occur. In a typical scenario, the rate at which path loss changes is much smaller than the rate at which shadow fading and fast fading occur. When discussing the propagation losses, it is common to use path loss, shadow and fast fading factors, which are defined as the reciprocals of the corresponding losses, with respect to mobile '*i*'.

5.2.1 Path Loss

Following the practice in the literature, a simple "power law" model is assumed to calculate the distance loss between a mobile and a base station. Assuming the mobile is located at a distance '*r*' away from the base station, the path loss factor d_i is given by:

$$d_i = br^{-\chi} \tag{5-1}$$

where b and χ are constants. Following common practice, the transmitter-decay law with exponent four is used.

5.2.2 Shadow Fading

Similar to the work in the literature, a lognormal distribution for the shadow-fading factor is assumed. In other words, its logarithm has a normal or Gaussian distribution. Gudmunson [1991] demonstrated the autocorrelation function of the logarithm of the shadow-fading factor can be adequately approximated by an exponential function with decay factor $-V/a$ where V is the speed of the mobile and a is the correlation length of the shadowing. Variable a is the distance a mobile has to travel before the autocorrelation of the logarithm of the shadow fading falls to e^{-1} times its peak value. Gudmunson [1991] also reports that a is of the order of 500 meters in suburban environments and 50 meters in urban environments. Using a sampling rate of 1.25 ms, the correlation coefficient f for the logarithm of the shadow-fading factor is given by [Chuah, Nanda & Rege, 1998]:

$$f = \left(\frac{-1.25 * 10^{-3} V}{a} \right) \tag{5-2}$$

where V is the speed of the mobile in meters/second and a the correlation length in meters. Shadow fading factor at time 'n' for mobile 'i' is generally expressed in terms of its standard deviation i.e.:

$$A_i(n) = C10^{\frac{\xi_i}{10}} \tag{5-3}$$

where C is the normalization constant and ξ_i is a zero mean Gaussian random variable with standard deviation σ = 6.3 watts (8dB) [Foschini & Miljanic, 1993]. The shadow fading factor $A_i(n)$ is then said to have a standard deviation of σ dB. Since the logarithm of the shadow-fading factor has a Gaussian distribution and the sampled instants have geometric autocorrelation, its samples can be generated as a first-order Gauss Markov process [Chuah *et al.*, 1998].

$$\xi_i(n+1) = f\xi_i(n) + w(n+1) \qquad \textbf{(5-4)}$$

where $w(n+1)$ is a white Gaussian noise sample which is independent of the history of the ξ_i up to the current sample. The correlation coefficient f is a desired one-step autocorrelation and w has a variance equal to $\sigma_w^2 = \sigma^2(1-f^2)$

5.2.3 Fast Fading

Fast fading is caused by multipath reflections of the original signal, which arrive at the receiver at different points in time, phase and Doppler frequencies. These multipath signals then give rise to a rapidly fluctuating signal level. The resulting signal amplitude has a Rayleigh distribution if there is no line-of-sight path between the transmitter and receiver and a Ricean distribution if there is a line-of-sight path between the transmitter and receiver. Frequency non-selective fast fading (flat fading) is modeled where the amplitude of the received signal is Rayleigh distributed. Rayleigh distributed variates are obtained as the magnitude of the variates having a complex Gaussian distribution. The propagation path is commonly assumed to be isotropic scattering received by a vertical monopole antenna. In this case, the real and imaginary parts of the time samples of the complex Gaussian processes each have autocorrelation sequence [Young & Beaulieu, 1998]:

$$r[s] = J_o\left(2\pi f_m |s|\right) \tag{5-5}$$

where f_m is the maximum Doppler frequency normalized by the sampling rate and s is the separation between samples. The real and imaginary parts of the complex sequence must be independent and each must have zero mean for Rayleigh fading.

A method where two independent zero-mean white Gaussian processes are filtered and added in quadrature to form a Rayleigh process is used. The linear filtering operation on the Gaussian samples yields samples, which also have a Gaussian distribution. The autocorrelation properties of the resulting sequences are determined by the choice of the filter. A similar filter to Young [1997] and Verdin & Tozer [1993] is used. It realizes the $J_o(.)$ correlation considered here as the number of taps goes to infinity. The finite impulse response filter of odd length L is given by:

$$h[n] = \begin{cases} \sqrt{f_m}\dfrac{\Gamma(3/4)}{\Gamma(5/4}, & n = \dfrac{L-1}{2} \\ \left(\dfrac{f_m}{\pi}\right)^{1/4} \Gamma(3/4)\left[n - \dfrac{L-1}{2}\right]^{-1/4} J_{1/4}\left(2\pi f_m\left[n - \dfrac{L-1}{2}\right]\right), & \\ & n = 0,1 \ldots\ldots, L-1, n \neq \dfrac{L-1}{2} \end{cases} \tag{5-6}$$

where $\Gamma(x)$ is the *Gamma function* defined as, $\Gamma(x) = \int_0^\infty f^{x-1}\, e^{-t} dt$ and $J_n(x)$ is the *Bessel function* defined as, $J_n(x) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \exp(jx\sin\theta - jn\theta) d\theta$.

5.3 System Model

A multicellular and multiservice CDMA system is considered. To each communication link, a pair of orthogonal channels for the mobile-to-base (uplink) and base-to-mobile (downlink) communication is allocated. Since there is no interference between the uplinks and the downlinks, in the model, only uplinks are considered for power control. However, the results can also be applied to downlinks.

5.3.1 SIR and Gain Calculation Model

Let P_{ij} be the power transmitted by the mobile '*i*' of class '*j*'. G_{ij} denotes the link gain from the mobile '*i*' to the base station. Following a more realistic approach, the receiver noise is also taken into account. Let η_o be the receiver noise due to all the other active mobiles, at the base station.

Thus, the signal-to Interference Ratio (SIR) at the base station at time '*n*' for mobile '*i*' belonging to service class '*j*' can be given as:

$$\Gamma_{ij}(n) = \frac{G_{ij}(n)P_{ij}(n)}{\sum_{j=1}^{J}\sum_{l \neq i}^{I_J} G_{lj}(n)P_{lj}(n) + \eta_o} \qquad \textbf{(5-7)}$$

where G_{ij} and P_{ij} are the link gains and transmitted power of mobile '*i*' of class '*j*' at time '*n*'. In equation (5-7) 'I_J' denotes the number of mobiles in the network belonging to service class '*J*'. Without loss of generality we will assume that the number of mobiles are the same in all classes of service i.e., $I_J = I$, $(0<j<J)$.

The link gain (in power units) of mobile '*i*' belonging to service class '*j*' at time '*n*' is given by:

$$G_{ij}(n) = \frac{A_{ij}(n)B_{ij}(n)}{d_{ij}^4} \quad \textbf{(5-8)}$$

where d_{ij} is the distance between the transmitter and the receiver (base station), $A_{ij}(n)$ is the correlated shadowing (lognormal) fading time process calculated as given in section 5.1.2; and $B_{ij}(n)$ is the correlated Rayleigh (fast) fading time process of mobile '*i*' of class '*j*' calculated as given in section 5.2.3.

The optimal SIR for each of the service classes (j) is different, thereby meeting different QoS and is tracked down by the mobiles themselves at time '*n*'. Let the target SIR to be met by mobiles belonging to each of the classes of service be denoted as $\Gamma_{oj}(n)$.

5.3.2 Interference – Mean & Variance Calculation Model

A stochastic on-off traffic sources, probabilistic quality of service specifications, an asymptotic scaling for wideband networks and a Gaussian approximation of the cell-dependent interference are some of the notions that are taken into account in the proposed distributed power control scheme.

The transmitted power of mobiles in each service class is based on the measurements of not only the mean of the local interference, which is conventional, but also on the variance of the interference caused by the other active mobiles. The updated powers take into account that both the signal propagation and the interference are random processes varying in time.

Let X_{ij} be the activity indicator of mobile '*i*' of service class '*j*', i.e., $X_{ij} \in \{0,1\}$ and $X_{ij} = 1$ if and only if the mobile is active at a point in time. Hence on considering the stochastic traffic model of a bursty mobile '*i*' of class service '*j*' to be on-off, i.e., in the cell '*c*'it is on (active), with probability w_{ijc} [Mitra & Morrison, 1996]. It can be given as:

$$w_{ijc} = \Pr\{X_{ij} = 1\} = 1 - \Pr\{X_{ij} = 0\} \tag{5-9}$$

In order to calculate the interference to an active mobile's transmission, we first let $R^m_{ijc}(n)$ denote the received power at cell site '*m*' due to all the active mobiles in cell '*c*' at time '*n*' i.e.,

$$\begin{aligned} R^m_{ijc}(n) &= \sum_{i \in (c,j)} G^m_{ijc}(n) P_{ijc}(n) X_{ijc} \\ &= P_{ijc}(n) \sum_{i \in (c,j)} \frac{g_{ijm}(n)}{g_{ijc}(n)} X_{ijc} \end{aligned} \tag{5-10}$$

where $G^m_{ijc}(n)$ is the link gain of mobile '*i*' of class '*j*' operating from cell '*c*' to cell site '*m*', $P_{ijc}(n)$ is the power transmitted by mobile '*i*' of class '*j*' in cell '*c*' and X_{ijc} is the activity indicator of mobiles in cell '*c*'. $g_{ijm}(n)$ and $g_{ijc}(n)$ represent the local gains. In isolating the components independent of power and denoting the term, which depends on relative gains and the random activity indicator as M^m_{ijc}, i.e.:

$$M^m_{ijc}(n) = \sum_{i \in (c,j)} \frac{g_{ijm}(n)}{g_{ijc}(n)} X_{ijc} \quad (1 \le m \le M, 1 \le c \le M, 1 \le i \le I, 1 \le j \le J) \tag{5-11}$$

Hence, $R^m_{ijc}(n) = P_{ijc}(n)\, M^m_{ijc}(n)$ and it is noted that:

$$M^m_{ijc}(n) = \sum_{i\in(c,j)} G^m_{ijc} X_{ijc} \tag{5-12}$$

The total power received at cell site '*m*' due to active mobiles in all the cells is, thus:

$$R^m_{ij}(n) = \sum_{j=1}^{J}\sum_{i=1}^{I} P_{ij}(n) M^m_{ij}(n) + \eta_o W \tag{5-13}$$

where W is the processing gain. Since a wideband system is considered, W is large. For any active mobile '*i*' of class '*j*', $X_{ij} = 1$ and the interference to its transmission is:

$$I^m_{ij}(n) = M^m_{ij}(n) - P_{ij}(n) \tag{5-14}$$

From equation (5-9), we get:

$$E(X_{ij}) = w_{ijc} \qquad \text{var}(X_{ij}) = w_{ijc}(1 - w_{ijc}) \tag{5-15}$$

Hence, from equation (5-11):

$$E(M^m_{ijc}(n)) = \sum_{i\in(c,j)} \frac{g_{ijm}(n)}{g_{ijc}(n)} w_{ijc}$$

$$= k_{jc} G^m_{ijc} w_{ijc} \tag{5-16}$$

where k_{jc} is the number of mobiles of class '*j*' in that particular cell '*c*', and,

$$G_{ijc}^{m}(n)=\frac{1}{k_{jc}}\sum_{i\in(c,j)}\frac{g_{ijm}(n)}{g_{ijc}(n)} \qquad \textbf{(5-17)}$$

From equations (5-13) and (5-16) the measured values of the mean of the total interference at cell site '*m*' from mobiles operating in the network at time period '*n*' can be given as:

$$I_{ij}^{m}(n)=\sum_{j=1}^{J}\sum_{i=1}^{I}G_{ij}^{m}(n)k_{j}w_{ij}P_{ij}(n)+\eta_{o}W \qquad \textbf{(5-18)}$$

where k_j and w_{ij} represent the number of mobiles of class '*j*' and the probability of the mobile to be active in *any cell*, respectively.

Similarly from equations (5-11) and (5-15), we get:

$$\begin{aligned}\operatorname{var}(M_{ijc}^{m}(n)) &= \sum_{i\in(c,j)}\left(\frac{g_{ijm}(n)}{g_{ijc}(n)}\right)^{2}w_{ijc}(1-w_{ijc})\\ &= k_{jc}(H_{ijc}^{m}(n))^{2}w_{ijc}(1-w_{ijc}) \qquad \textbf{(5-19)}\end{aligned}$$

Thus, the measured values of the variance of the total interference at cell site '*m*' can be given as:

$$V_{ij}^{m}(n)=\sum_{j=1}^{J}\sum_{i=1}^{I}(H_{ij}^{m}(n))^{2}k_{j}w_{ij}(1-w_{ij})P_{ij}^{2}(n) \qquad \textbf{(5-20)}$$

where $H_{ij}^{m}(n)=\frac{1}{k_{j}}\sum_{j=1}^{J}\sum_{i=1}^{I}(G_{ij}^{m}(n))^{2}$ **(5-21)**

From this section onwards, it will be assumed that all the variables are referred with respect to base station '*m*'. Thus, the superscript '*m*' will be dropped. Both these values i.e., the mean of the total interference and the variance of the total interference, are used in the Power Control Scheme and the SIR Adaptation Algorithm.

5.4 Power Control Scheme

Sketched in Figure 5-1, is the block diagram of the proposed closed-loop variable step size power control system. It helps in the understanding of the working of both the power control and SIR adaptation schemes that are derived in the following sections, with more clarity. The proposed scheme comprises of two loops – an outer loop and an inner loop. The outer loop computes and adapts the target SIR and the inner loop assigns transmission powers to track the provided target SIR while compensating for the channel attenuations.

Variables like the threshold SIR $\Gamma_{oj}(n)$, measured SIR $\Gamma_{ij}(n)$, the total interference $I_{ij}(n)$, the total variance $V_{ij}(n)$ and the variable step size are all measured and calculated at the base station. A multi-step (variable) power control command is issued from the base station to a mobile unit. An error could occur in the command while it is sent on the downlink channel from the base station to the mobile, as represented by the "channel error on command". Channel variation is used to describe how a transmitted signal is affected by conditions such as fading, interference, or noise, while it is transmitted through the channel. The error signal, denoted by ε, inside the base station serves as an indicator to indicate whether the SIR measurement taken at the base station is above (when $\varepsilon > 0$) or below (when $\varepsilon < 0$) the threshold $\Gamma_{oj}(n)$.

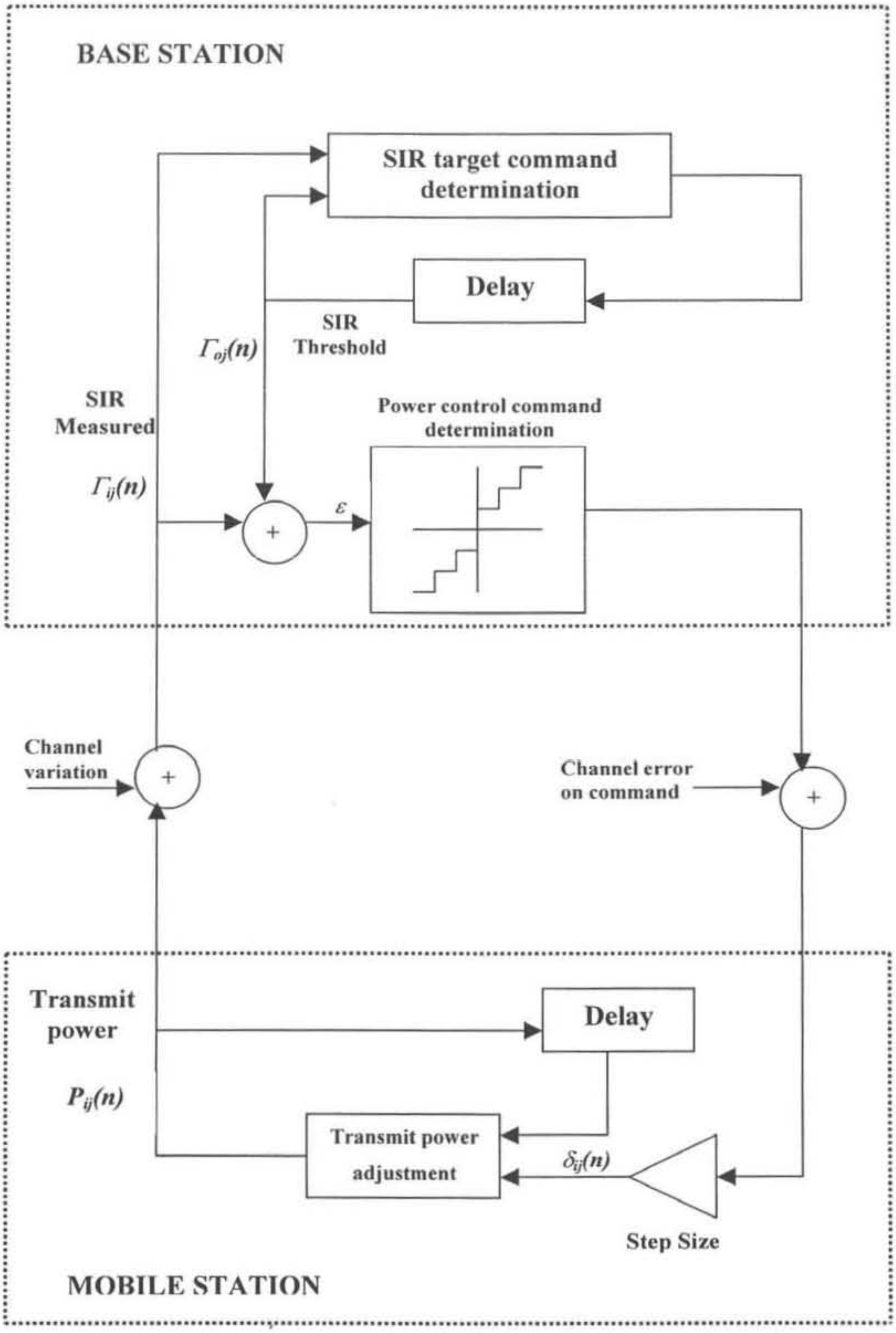

Figure 5-1 Block Diagram of Variable Step Size Power Control

Following the rules given in the proposed variable step size algorithm, the mobile is asked to raise or lower its transmitted power. The transmit power adjustments are done at the mobile station. This is always done in a symmetric manner [Ariyavisitakul & Chang, 1993], [Ariyavisitakul, 1992], [Ariyavisitakul, 1994b].

The proposed power control scheme is a discrete-time feedback adjustment power control scheme. For the uplink, the transmitted power of the mobile '*i*' is to be adjusted to meet with the required SIR of that particular class '*j*', at the corresponding base station.

A target window of SIR for each of the service classes, as computed by the SIR adaptation algorithm ($\Gamma_{oj}(n)$), is used as reference. If the SIR $\Gamma_{ij}(n)$, as measured by the base station (given by equation (5-7)), of the active mobile '*i*' of class '*j*' at time '*n*' is below the window, the base station will inform the mobile to raise its transmitted power by the required step. The mobile, following the instructions of the base station will increase the transmitted power P_{ij} at time '*n+1*'. If the SIR $\Gamma_{ij}(n)$, is above the target window ($\Gamma_{oj}(n)$) at time '*n*', the power will be adjusted downward by the required step, and if the power falls within the target window, the power will remain unchanged i.e., the mobile will transmit at the same transmitted power P_{ij} at time '*n+1*'.The given variable-step size power control algorithm summarises these procedures.

Each mobile unit adjusts and updates its transmitted power P_{ij} in the $(n+1)^{th}$ step accordingly as:

$$P_{ij}(n+1) = \begin{cases} \delta_{ij}(n)P_{ij}(n) & \text{if} \quad \Gamma_{ij}(n) < \delta_{ij}^{-1}(n)\Gamma_{oj}(n) \\ \delta_{ij}^{-1}(n)P_{ij}(n) & \text{if} \quad \Gamma_{ij}(n) > \delta_{ij}(n)\Gamma_{oj}(n) \\ P_{ij}(n) & \text{Otherwise.} \end{cases}$$

(5-22)

where $\delta_{ij}(n)$ is the step size by which power transmitted by mobile '*i*' of class '*j*' is adjusted in the next time frame $(n+1)$.

The step size is related to the variance and the mean of the total interference caused by all the active mobiles belonging to the different classes of service operating in all the cells. Using the values of the mean and variance of the total interference from equations (5-18) and (5-20), the step size can be calculated as follows:

$$\delta_{ij}(n) = \delta_{ij}^{*} + k_o \left(\frac{\sqrt{V_{ij}(n)}}{I_{ij}(n)} \right) \qquad \textbf{(5-23)}$$

where δ_{ij}^{*} and k_o are constants. This variable step size power control algorithm helps in the fast convergence of the SIR to the assigned value ($\Gamma_{oj}(n)$) and this can be attributed to the constant k_o also. Results obtained help us to conclude that higher the value of k_o, faster is the convergence of SIR to the desired target value.

Some of the main features of the proposed power control algorithm are:

- The only information needed to adjust the transmission power of the mobile terminal is the received SIR at the corresponding base station.

- Coordination among the base stations is not required.

- It is insensitive to the SIR estimation error because the power change depends on a simple comparison rule.

- Simple and easy to implement.

5.5 SIR Adaptation Algorithm

The SIR adaptation algorithm characterizes the mobiles belonging to different service classes by distinctive QoS parameters. These QoS parameters define the desired minimum SIR level to be satisfied. It provides a framework for estimating the order of the magnitude of quantities, which affect the QoS.

The quality of service requirement in terms of the signal-to-interference ratio can be given as:

$$\frac{R_{ij}(n)}{I_{ij}(n)} \geq \frac{\alpha_j}{W} \tag{5-24}$$

where $R_{ij}(n)$ denotes the power received at the base station of mobile '*i*' belonging to class '*j*' and $I_{ij}(n)$ the total interference caused by all the mobiles at time '*n*'. $\{\alpha_j\}$ are prespecified QoS numbers for each service class; the right hand quantity is typically small, since the processing gain W is large.

On account of the random source behaviour, the QoS requirement has to be probabilistic in nature, with some probability of compliance at best less than unity. This requirement can be given as:

$$\Pr\left\{R_{ij}(n) \geq \frac{\alpha_j}{W} I_{ij}(n)\right\} \geq 1 - L_j \tag{5-25}$$

where $\{L_j\}$ are given parameters for different classes of service.

Inherent to wideband systems in which the bandwidth (W) is shared by a large number of users is the following asymptotic scaling, in which the large parameter K is the average number of mobiles in a cell, i.e., $K = \frac{1}{C}\sum_{c=1}^{C}\sum_{j=1}^{J} k_{jc}$.

$$\frac{\alpha_j}{W} = \frac{a_j}{K}, \qquad k_{jc} = \beta_{jc} K \tag{5-26}$$

where $a_j = O(1)$ and $\beta_{jc} = O(1)$ as $K \to \infty$ and $W \to \infty$. We note that α_j and η_o are other O(1) parameters. With a small loss of generality, we consider these O(1) parameters to be fixed in this scaling. W and K are of the same order. Let:

$$R_{ijc}(n) = \hat{R}_{ijc}(n) + \frac{1}{\sqrt{K}} Q_{ijc} \tag{5-27}$$

where $\hat{R}_{ijc}(n)$ and Q_{ijc} are O(1). The orders of magnitude of the first order (dominant) and second order terms in the above expansion of $R_{ijc}(n)$ are dictated by consistency.

On investigating the implications of equations (5-26) and (5-27) on the terms $R_{ijc}(n)$ and $\alpha_j I_{ij}(n)$ appearing in the quality of service specifications in equation (5-25), we substitute equations (5-26), (5-27) in the expansion of equation (5-13) and get:

$$\frac{\alpha_j}{W} I_{ij}(n) = a_j \sum_{c=1}^{C}\sum_{j=1}^{J} G_{ijc}(n)\, \beta_{jc}\, w_{ijc}\, \hat{R}_{ijc}(n) + \alpha_j \eta_o$$

$$+ \frac{a_j}{\sqrt{K}} \sum_{c=1}^{C}\sum_{j=1}^{J} \left[G_{ijc}(n)\, \beta_{jc} w_{ijc} Q_{ijc} + H_{ijc} \sqrt{\beta_{jc} w_{ijc}(1 - w_{ijc})} Z_{ijc} \hat{R}_{ijc}(n) \right] + O\left(\frac{1}{K}\right) \tag{5-28}$$

where $i \in (c, j)$

To achieve $R_{ij}(n) \geq \alpha_j I_{ij}(n)/W$, we first compare the order 1 terms and, then the coefficients of $1/\sqrt{K}$ to obtain the system of inequalities given below in equations (5-29) and (5-30) respectively. These constitute sufficient condition to given $R_{ij}(n) \geq \alpha_j I_{ij}(n)/W$ to within O(1/*K*).

$$\hat{R}_{ijc}(n) - \frac{\alpha_j}{W}\sum_{c=1}^{C}\sum_{j=1}^{J} G_{ijc}(n) k_{jc} w_{ijc} \hat{R}_{ijc}(n) \geq \alpha_j \eta_o, \quad i \in (c, j) \tag{5-29}$$

and $$Q_{ijc} - \frac{\alpha_j}{W}\sum_{c=1}^{C}\sum_{j=1}^{J} G_{ijc}(n) k_{jc} w_{ijc} Q_{ijc} \geq a_j \xi_j, \quad i \in (c, j) \tag{5-30}$$

where $$\xi_j = \sum_{c=1}^{C}\sum_{j=1}^{J} H_{ijc}(n)\sqrt{\beta_{jc} w_{ijc}(1 - w_{ijc})} Z_{ijc} \hat{R}_{ijc}(n), \quad i \in (c, j) \tag{5-31}$$

Equations (5-29) and (5-30) are systems of relations, which differ qualitatively in that equation (5-29) is purely deterministic while equation (5-30) contains random variables in its right hand side. In matrix form equation (5-29) is:

$$\hat{\mathbf{R}}(\mathrm{n}) - \frac{\alpha_j}{\mathrm{W}} \mathbf{F}(\mathrm{n})\hat{\mathbf{R}}(\mathrm{n}) \geq \alpha_j \boldsymbol{\eta}_o \tag{5-32}$$

where $$F_{ijc}(n) = G_{ijc}(n) k_{jc} w_{ijc} \tag{5-33}$$

$\hat{\mathbf{R}}(\mathrm{n}) = \{\hat{R}_{ijc}(n)\}$ and $\mathbf{F}(\mathrm{n}) = \{F_{ijc}(n)\}$. Thus, $F_{ijc}(n)$ is the mean value of the power-independent, random component $M_{ijc}^{m}(n)$ (in equation (5-11)). It is hence reasonable to call **F**(n) an *intercellular gain matrix.*

$$R_{ij}(n+1) = \frac{\alpha_j}{W}\left[I_{ij}(n) + v_j\sqrt{V_{ij}(n)}\right] \quad \textbf{(5-38)}$$

The SIR of mobile '*i*' of class '*j*' at time period $(n+1)$ is adapted based on the received power at $(n+1)$ as:

$$\Gamma_{oj}(n+1) = \frac{R_{ij}(n+1)}{I_{ij}(n)} \quad \textbf{(5-39)}$$

This SIR value, typically defining the QoS objectives for each service class, is to be met with by the mobiles by regulating their transmitted power using the variable step size power control algorithm.

5.6 Simulation Model

The events mentioned above can occur at specific times, random times, or sequentially, and may or may not depend on one another. These events generally occur relative to a frame reference. We use a time frame structure wherein the simulator starts at some reference time 'N_start' and ends at some arbitrary time 'N_limit'. There are two possible ways of incrementing the reference time in a simulator. The first method is to continuously increment the reference time by a fixed infinitesimal amount. The events are then processed whenever the times at which they occur match the reference time. This process is called a *continuous time* simulator.

The second method increments the reference time only when the next event occurs. In other words, if the simulator is at time t and the next event occurs at time $t+\lambda$, the simulator automatically increments its reference time to $t+\lambda$. This type of simulator is commonly labeled an *event-driven* simulator. An advantage of this approach over the continuous time simulator is a reduction in running time. For example, if λ is large, the processor does not waste time incrementing its reference time until the next event. Thus event-driven simulators result in faster simulations and are generally preferred when the simulation models are large and complex. We therefore model an event-driven simulator in this study.

5.6.1 Cellular Structure

An ideal network structure would consist of a very large number of cells. However, simulation of such a system is impractical. An alternative approach is to use few cells that adequately approximate the large network. A square grid layout of the system is assumed as shown in Figure 5-2.

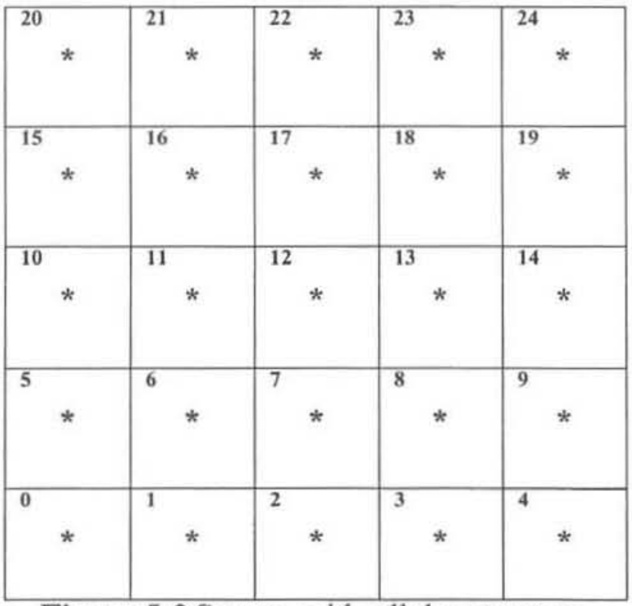

Figure 5-2 Square-grid cellular structure

Figure 5-2 illustrates a network that consists of 25 cells with a base station (*) centrally located in each cell. The same kind of result can be obtained if a hexagonal cellular structure is modeled.

5.6.2 Flow Diagram of Software Simulator

This section describes the actual layout of the event-driven software simulator. Each event is described below and is performed by a specific subroutine. The events are categorized as follows:

- Shadow fading - *SLOW_FADING subroutine*
- Rayleigh fading - *FAST_FADING subroutine*
- Link gain - *LINK_GAIN subroutine*
- SIR measurement - *SIR_CALCULATION subroutine*
- Mean of interference - *INT_MEAN subroutine*
- Variance of interference - *INT_VARIANCE subroutine*
- Step size - *STEP_SIZE subroutine*
- Power control - *POWER_CONTROL subroutine*
- Received power - *REC_POW_ADAPT subroutine*
- Target SIR - *TARGET_SIR_ADAPT subroutine*
- Simulation results - *STATISTICS subroutine*

The simulator starts at time n=N_start and ends at some arbitrary time n=N_limit. The software platform used is C++. We summarise below the assumptions that are made in the simulation.

- Numerical performance results are given for the case where user has only one service class and all users belonging to the same class of service request the same QoS.
- The mobile users are randomly located in the system but with a uniform density of users per base station.
- The mobile users remain at different fixed position throughout the simulation run.

5.6.2.1 Diagram of Software Simulator

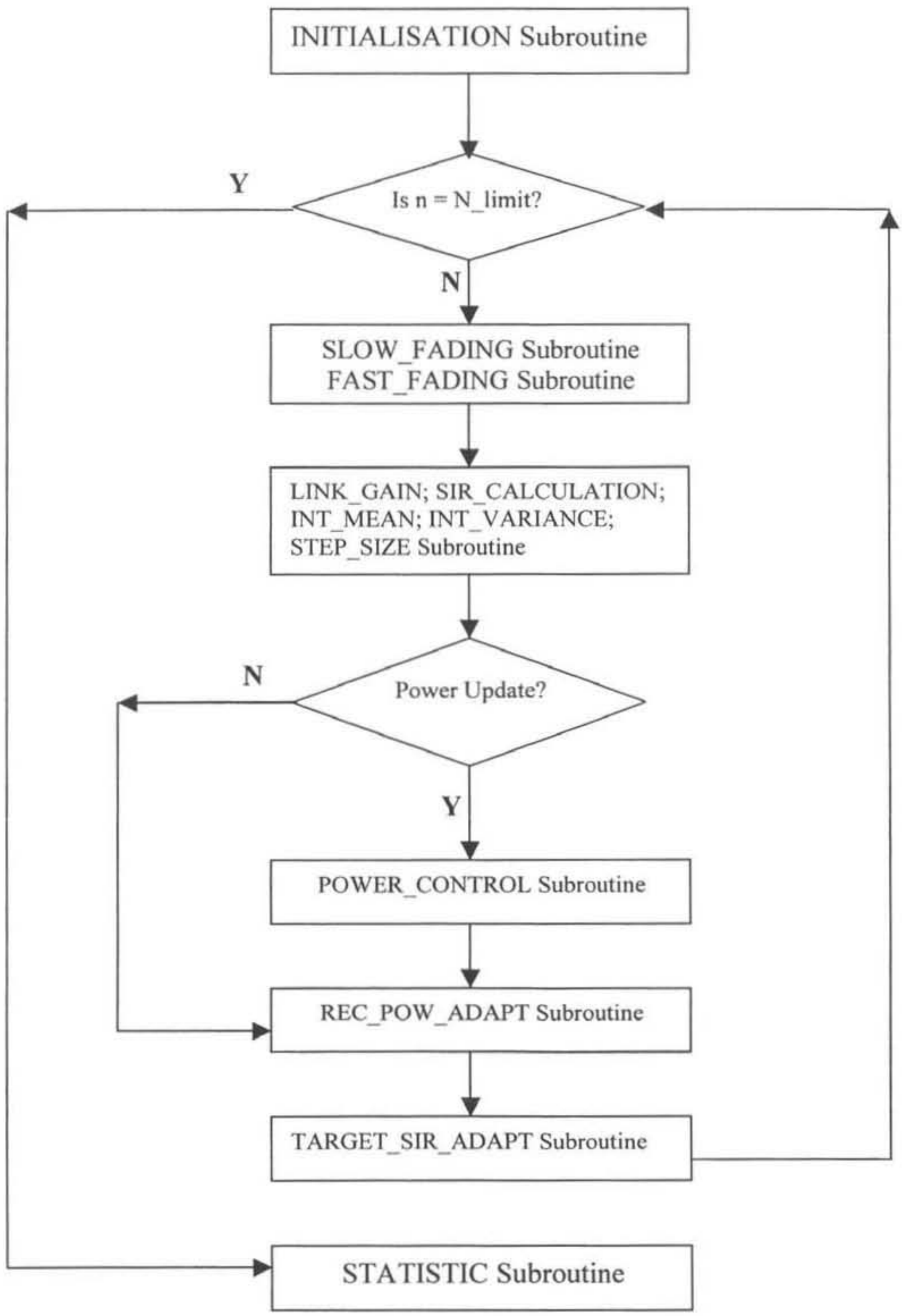

Figure 5-3 Flow Diagram of Main Routine.

Figure 5-3 illustrates a flow diagram of the main routine

5.6.2.2 SLOW_FADING Subroutine

In this subroutine, the simulator generates new shadow fading parameters $\xi_{ij}(n+1)$ based on the previous shadow fading parameter $\xi_{ij}(n)$, the correlation coefficient f and random variable $w(n+1)$ normally distributed with zero mean and standard deviation σ_w. We generate $w(n+1)$ using the Box-Muller method [Bratley, Fox & Schrage, 1983]. The slow fading parameter is deterministically determined between a mobile and it's communicating base station and is computed for all the mobiles belonging to different classes of service, in the network.

SLOW_FADING Subroutine

For each cell

For each class *j*

For each mobile *i*

Calculate correlation coefficient $f = \left(-1.25*10^{-3} V/a\right)$

Determine σ_w^2 **from** $\sigma_w^2 = \sigma_w^2 = \sigma^2\left(1-f^2\right)$

Generate random variable U_1 uniformly distributed between 0 and 1

Generate random variable U_2 uniformly distributed between 0 and 1

Calculate $w(n+1) = \sigma_w \cos(2\pi U_1)\sqrt{-2\ln(U_2)}$

Determine $\xi(n+1) = f\xi(n) + w(n+1)$

Compute $A_{ij}(n+1) = C10^{\frac{\xi(n+1)}{10}}$

Store relevant information

End for

End for

End for

5.6.2.3 FAST_FADING Subroutine

In this subroutine, the simulator deterministically generates frequency non-selective fast fading parameters for all the mobiles in the network. Rayleigh fading is generated from two normally distributed random variables X_1 and X_2. The two white Gaussian noise processes are then filtered and added in quadrature to form a Rayleigh process. A filter similar to the one used by Young [1997] and Verdin & Tozer [1993] is chosen where the finite impulse response of the filter is as given in equation (5-6).

FAST_FADING Subroutine

For each cell

For each class *j*

For each mobile *i*

Generate random variable U_1 uniformly distributed between 0 and 1

Generate random variable U_2 uniformly distributed between 0 and 1

Calculate Gaussian random variable $X(n+1) = \sigma \cos(2\pi U_1)\sqrt{-2\ln(U_2)}$

Convolve $X(n+1-L) \rightarrow X(n+1)$ **with impulse response of filter to obtain** X

Generate random variable U_3 uniformly distributed between 0 and 1

Generate random variable U_4 uniformly distributed between 0 and 1

Calculate Gaussian random variable $Y(n+1) = \sigma\cos(2\pi U_3)\sqrt{-2\ln(U_4)}$

Convolve $Y(n+1-L) \rightarrow Y(n+1)$ **with impulse response of filter to obtain** Y

Compute $B_{ij}(n+1) = \dfrac{1}{\sqrt{X^2 + Y^2}}$

Shift $X(n) \rightarrow X(n-1)$ **and** $Y(n) \rightarrow Y(n-1)$

Store relevant information

End for

End for

End for

5.6.2.4 LINK_GAIN Subroutine

The channel link gain from a mobile to its base station is calculated using this subroutine. The correlated lognormal (shadow) fading, correlated Rayleigh (fast) fading and path loss of the mobile user from its assigned base station, are retrieved from the appropriate tables, and the routine calculates the link gain accordingly as given in equation (5-8).

LINK_GAIN Subroutine

....

For each cell

For each class ***j***

For each mobile ***i***

Calculate actual (x,y) position of mobile

Calculate the distance of mobile from base station d_{ij}

Retrieve slow fading $A_{ij}(n)$ **and fast fading** $B_{ij}(n)$ **parameters from tables**

Compute link gain $G_{ij}(n) = \dfrac{A_{ij}(n)B_{ij}(n)}{d_{ij}^4}$

Store relevant information

End for

End for

End for

5.6.2.5 SIR_CALCULATION Subroutine

In this subroutine, the simulator calculates the Signal-to-Interference ratio of a mobile belonging to a service class as measured by the base station. The simulator retrieves the link gain and the transmitted power values from the tables to do so. The receiver noise due to all the other active mobiles is also taken into account. The value of the receiver noise is kept constant and is retrieved from the initialization subroutine. The SIR value of the mobile user belonging to different classes of service is calculated at each time interval as given in equation (5-7).

SIR_CALCUATION Subroutine

For each cell

For each class j

For each mobile i

Retrieve link gain $G_{ij}(n)$ **from tables**

Retrieve user transmit power $P_{ij}(n)$

Retrieve receiver noise η_o

Retrieve values of mobile m **of class** a

For each a

For each $m \neq i^{th}$ **user**

Calculate $sum\_plus = G_{ma}(n)P_{ma}(n)$

Compute $A = (sum\_plus) + \eta_o$

End for

End for

Compute SIR $\Gamma_{ij}(n) = \dfrac{G_{ij}(n)P_{ij}(n)}{A}$

Store relevant information

End for

End for

End for

5.6.2.6 INT_MEAN Subroutine

In this subroutine, the mean of the total interference caused by the other active mobiles belonging to different classes of service operating in all the cells is calculated. Preset values like the processing gain, the total receiver noise and the number of mobiles of that particular class operating in that cell are all recalled from the initialisation subroutine. The probability of a mobile to be in active state is kept high. It is set at a value of 0.9. The subroutine calculates the mean value of the total interference as given by equation (5-18)

INT_MEAN Subroutine

....

For each cell

For each class *j*

For each mobile *i*

Retrieve user link gain $G_{ij}(n)$ **from tables**

Retrieve user transmit power $P_{ij}(n)$

Retrieve processing gain W

Retrieve number of mobiles of that service class operating in the same cell k_j

Retrieve receiver noise η_o

Retrieve value of probability of mobile to be in active sate w_{ij}

Retrieve values of mobile m **of class** a

For each a

For each $m \neq i^{th}$ **user**

Compute $sum\_plus = G_{ma}(n)k_a w_{ma} P_{ma}(n)$

End for

End for

Calculate Interference_Mean $I_{ij}(n) = (sum\_plus) + \eta_o W$

Store relevant information

End for

End for

End for

5.6.2.7 INT_VARIANCE Subroutine

The variance of the total interference caused by all the active mobiles present in all the cells, categorized based on their QoS requirements into different classes, is calculated in this subroutine. The subroutine recalls the values of the number of mobiles present in that particular cell belonging to the same class of service and the probability of a mobile to be in active state from the initialisation subroutine. The variance of the total interference is then calculated as given in equations (5-20) and (5-21).

INT_VARIANCE Subroutine

For each cell

For each class ***j***

For each mobile ***i***

Retrieve user link gain $G_{ij}(n)$

Retrieve user transmit power $P_{ij}(n)$

Retrieve number of mobiles of that service class operating in the same cell k_j

Retrieve value of probability of mobile to be in active sate w_{ij}

Retrieve values of mobile m **of class** a

For each a

For each $m \neq i^{th}$ **user**

Calculate $sum\_plus = G_{ma}^2(n)$

Compute $H_{ma} = \frac{1}{k_m}(sum\_plus)$

End for

End for

For each a

For each $m \neq i^{th}$ ***user***

Calculate $A = H_{ma}^2 k_m w_{ma}(1 - w_{ma})P_{ma}^2(n)$

End for

End for

Calculate Interference_variance $V_{ij}(n) = A$

Store relevant information

End for

End for

End for

5.6.2.8 STEP_SIZE Subroutine

In this subroutine, the step size by which the transmitted power of the mobile is to be adjusted is computed. The constants are recalled from the initialisation subroutine and the values of the mean and the variance of the total interference as calculated at the same time instant are retrieved. The step size is calculated as given in equation (5-23).

STEP_SIZE Subroutine

For each cell

For each class j

For each mobile i

Retrieve constants δ_{ij}^* and k_o from tables

Retrieve mean $I_{ij}(n)$ and variance $V_{ij}(n)$ of interference

Compute step size $\delta_{ij}(n) = \delta_{ij}^* + k_o\left(\frac{\sqrt{V_{ij}(n)}}{I_{ij}(n)}\right)$

Store relevant information

End for

End for

End for

5.6.2.9 POWER_CONTROL Subroutine

The power control algorithm is a deterministic event and occurs at a very fast rate in order to counteract fast fading. The strength-based closed loop power control algorithm that is updated approximately ten times faster than the maximum expected fading rate, is modeled. At each power update, the simulator retrieves the signal-to-interference ratio as measured at the base station, from the appropriate tables, and compares this value to the target SIR as obtained from the TARGET_SIR_ADAPT subroutine in the previous time interval. The subroutine then changes the mobiles' transmit power accordingly as stated in equation (5-22). In practice, it is rarely found that a power update is not required, or in other words, the mobile user is asked to transmit at the same power. This may be largely attributed to the channel attenuation between the mobile and its communicating base station.

POWER_CONTROL Subroutine

For each cell

For each class *j*

For each mobile *i*

Retrieve step size $\delta_{ij}(n)$

Retrieve user transmit power $P_{ij}(n)$

Retrieve measured SIR $\Gamma_{ij}(n)$

Retrieve target SIR $\Gamma_{oj}(n)$

If $\Gamma_{ij}(n) \neq \Gamma_{oj}(n)$

If $\Gamma_{ij}(n) < \delta_{ij}^{-1}(n)\Gamma_{oj}(n)$

$P_{ij}(n+1) = \delta_{ij}(n)P_{ij}(n)$

Else

If $\Gamma_{ij}(n) > \delta_{ij}(n)\Gamma_{oj}(n)$

$P_{ij}(n+1) = \delta_{ij}^{-1}(n)P_{ij}(n)$

Else

User transmit is unchanged

Store relevant information

End for

End for

End for

5.6.2.10 REC_POW_ADAPT Subroutine

In this subroutine, the received power of the mobiles belonging to the different classes of service is adapted at time $(n+1)$. The received power is adapted as given by equations (5-37) and (5-38). Both the parameters, which determine the

QoS requirements of a mobile, are predetermined values. α_j and v_j (as derived from L_j) are preset and are retrieved from the initialisation subroutine along with the values of both the mean and the variance of the total interference.

REC_POW_ADAPT Subroutine

For each cell

For each class *j*

For each mobile *i*

Retrieve values of α_j and L_j

Retrieve processing gain W

Retrieve mean $I_{ij}(n)$ and variance $V_{ij}(n)$ of interference

Calculate v_j from $1 - L_j = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{v_j} e^{\frac{-y^2}{2}} dy$

Compute received power

$$R_{ij}(n+1) = \frac{\alpha_j}{W}\left[I_{ij}(n) + v_j\sqrt{V_{ij}(n)}\right]$$

Store relevant information

End for

End for

End for

5.6.2.11 TARGET_SIR_ADAPT Subroutine

The target signal-to-interference ratio is adapted in this subroutine. The received power at time $(n+1)$ is used to adapt the target SIR. The subroutine retrieves the received power at $(n+1)$ and the mean of the interference value from the tables. The target SIR is calculated as given in equation (5-39).

TARGET_SIR_ADAPT Subroutine

For each cell

For each class j

For each mobile i

Retrieve user adapted received power $R_{ij}(n+1)$

Retrieve mean of interference $I_{ij}(n)$

Calculate target SIR $\Gamma_{oj}(n+1) = \dfrac{R_{ij}(n+1)}{I_{ij}(n)}$

Store relevant information

End for

End for

End for

Exit

5.6.2.12 STATISTICS Subroutine

When obtaining network results, the simulator averages the network statistics over the interval (N_start → N_limit). For different values of v_j and k_o performance graphs are obtained with respect to the Received SIR, Ripple Magnitude and Delta. Results of the Received SIR and the Received Power with respect to time are also obtained. This subroutine stores the relevant data for obtaining the performance graphs.

5.7 Simulation Parameters

The following simulation parameters were used in the simulation. These parameters shall be used throughout this thesis, unless otherwise specified.

Item	Value
Number of cells in network	25
Cell Radius	0.5 Km
Total Number of Mobiles	500
Classes of Service	3
Number of mobiles belonging to the same class operating in the same cell	7
Processing gain	63

Table 5-1 Network lay out parameters

Item	Value
Initial transmit power vector	0.63 watts
Receiver noise	10^{-6}
Probability of mobile to be active	0.9
QoS parameter α_1, α_2, and α_3	10, 1000 and 5000.
Step size constant δ_{ij}^{*}	10^{-3}

Table 5-2 Network model parameters

Item	Value
Path Loss	χ=4 b=1.2589x10^{-11} Update Rate = 1 s
Slow Fading	Mean = 0 dB Standard Deviation = 6.3 watts (8 dB) Update Rate = every 91 ms
Fast Fading	Mean = 0dB Standard Deviation = 10 watts (10dB) Update Rate = every 13 ms

Table 5-3 Fading model parameters

5.8 Results

In this section the results obtained from the simulation are presented. As stated, the main aim is to control the transmitted power of each of the mobiles so that at the base station the same power level is received from each mobile of that class. The speed, at which the powers of the mobile users are regulated and controlled, depends largely on the algorithm proposed which designs the step size δ. The step size is required not only to adjust the transmitted powers of the mobile users so as to meet with their QoS requirements, but also to follow slow lognormal shadowing, propagation loss as well as mitigate variations caused by fast fading. The simulation is run for a long time so as to show that the power level can still be kept in a finite range.

Performance results are obtained and studied for different values of k_o and v_j for all the mobiles belonging to the different classes of service. Results of the Received SIR, Ripple Magnitude and Delta as a function of v_j for different k_o values are obtained. The result of the variable step size power control is also compared to that obtained when a fixed step power control is implemented in the network.

5.8.1 Performance results for mobiles of class I

The following results were obtained for a mobile of class I. A case where the QoS requirement of the mobiles is not very high is considered.

5.8.1.1 Received Signal-to-Interference Ratio

Figure 5-4 illustrates the Signal-to-Interference ratio of a mobile belonging to class I as received at the base station, versus QoS parameter v_I for different step size constant k_o values. The QoS parameter α_I for mobiles of service class I is set to a value of 10. Simulations are run with k_o as 0.01, 0.1 and 0.5.

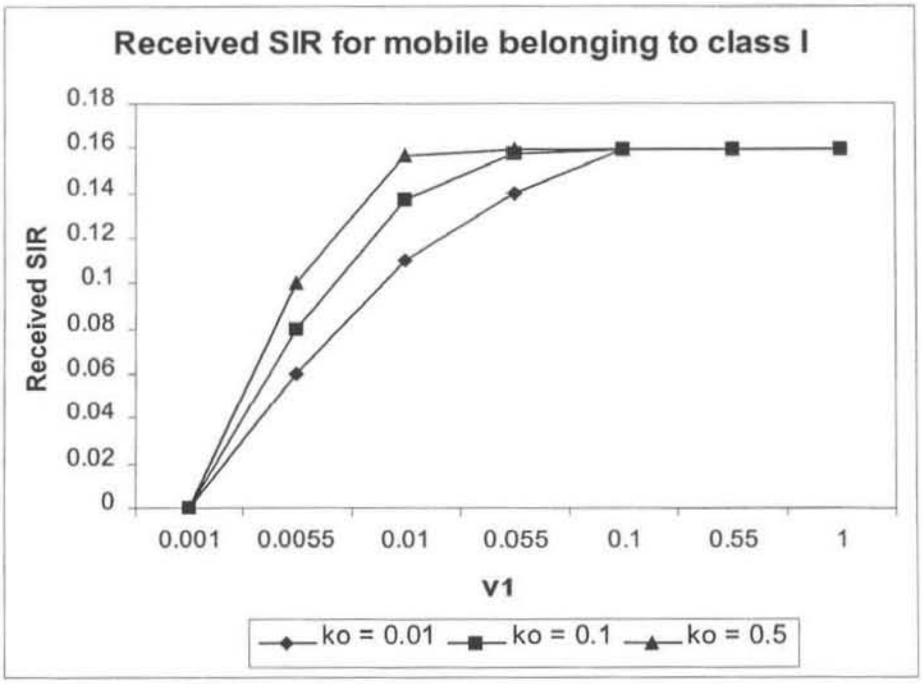

Figure 5-4 Received SIR vs. v_I for different k_o values (class I)

The graph clearly indicates that the SIR meets with the required set of value α_l/W (0.159) for all the three different k_o values. It can be noted that as k_o value is increased, the SIR converges at the required level faster even for a smaller set v_l. The main aim of providing the mobiles with their QoS demands, defined in terms of α_l and v_l is achieved.

5.8.1.2 Ripple Magnitude

Ripple magnitude is a measure by which the signal received at the base station varies about its mean target value.

Figure 5-5 illustrates the Ripple Magnitude of the received SIR signal versus v_l for different k_o values. It can be seen from the results obtained that, with a small k_o value, the ripple magnitude is also small though converging at a higher v_l value. As the k_o value increases, the ripple magnitude shoots up to a much higher level initially but later converging within an acceptable window, thereby stabilizing the system. Moreover, this convergence is seen at a lower v_l value.

This makes us to conclude that though a high k_o value helps in the fast convergence of the received SIR to its target value (Figure 5-4), thereby allowing the mobiles to meet with their QoS demands, a slight compromise on the ripple magnitude of the SIR needs to be made. The compromise is however of a small margin and is to be made at an initial stage only.

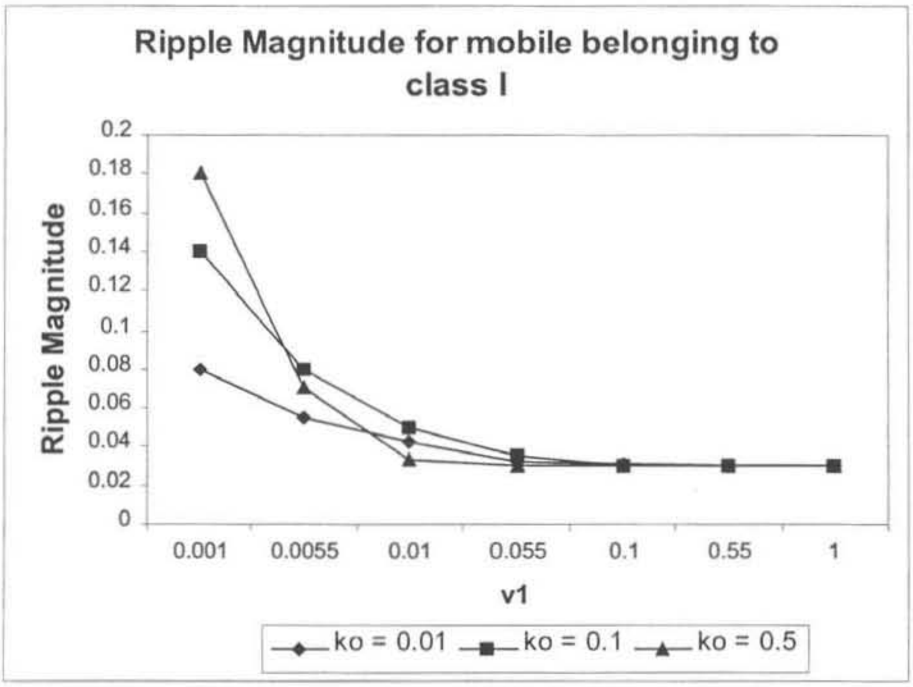

Figure 5-5 Ripple Magnitude vs. v_I for different k_o values (class I)

5.8.1.3 Delta (Step Size)

Delta (δ) as designed by the proposed power control scheme adjusts the transmitted power of the mobile, with each iteration, following the rules given in the power control algorithm. As stated earlier, in case the received SIR ($\Gamma_{ij}(n)$) is greater than the adapted target SIR ($\Gamma_{oj}(n)$), the transmitted power of the mobile at time $(n+1)$ is decreased by $\delta(n)$. While on the other hand if $\Gamma_{ij}(n)$ is less than $\Gamma_{oj}(n)$, the transmitted power of the mobile user is increased by $\delta(n)$.

Figure 5-6 indicates that δ controls the transmitted power efficiently by adjusting it to meet with the required SIR level, corresponding to the results obtained in Figure 5-4. It plays a major role in stabilizing the system by regulating the ripple magnitude. Corresponding to the case where k_o is of a high value, resulting in a high ripple magnitude initially, Delta is able to successfully help in its convergence and ultimately in the convergence of received SIR signal to the desired value.

Thus, the fact that the SIR is able to converge at a much faster rate to its required level and also at a lower v_1 value can be largely attributed to Delta and a high k_o value.

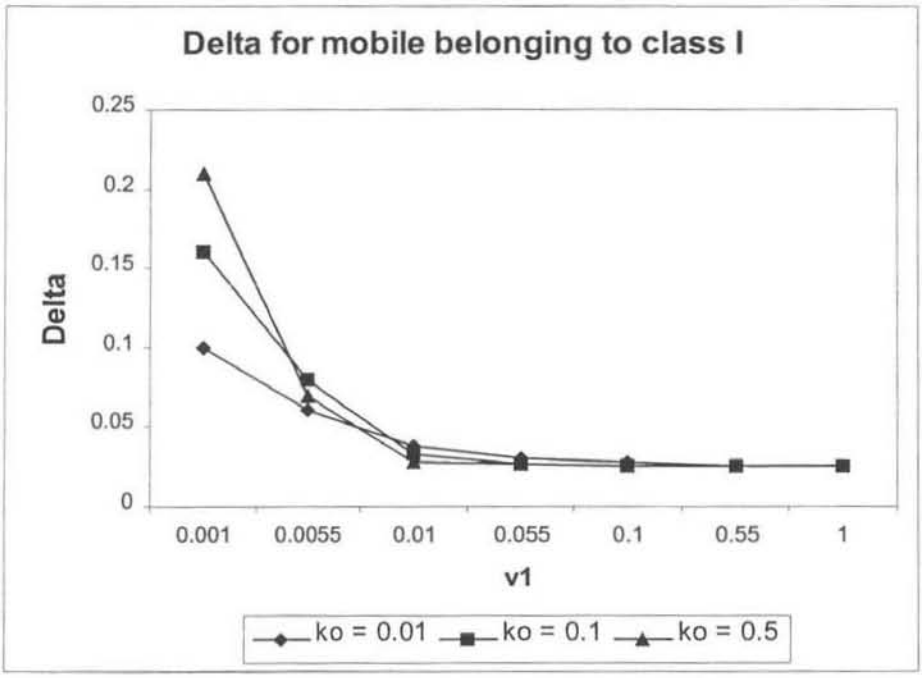

Figure 5-6 Delta vs. v_1 for different k_o values (class I)

5.8.2 Performance results for mobiles of class II

The following results are obtained for a mobile belonging to service class II. This category of mobiles neither requires too low nor very high QoS.

5.8.2.1 Received Signal-to-Interference Ratio

Figure 5-7 illustrates the Signal-to-Interference Ratio as received at the base station from a mobile of class II versus QoS parameter v_2. Results are obtained corresponding to the case where α_2 is set to a value of 1000. The graph is obtained for different k_o values.

The received SIR converges to the desired level of α_2/W (15.87). The graph indicates a similar response with k_o as obtained by the mobile of class I. The mobiles meet with both the QoS requirements, which are defined in terms of α_2 and v_2.

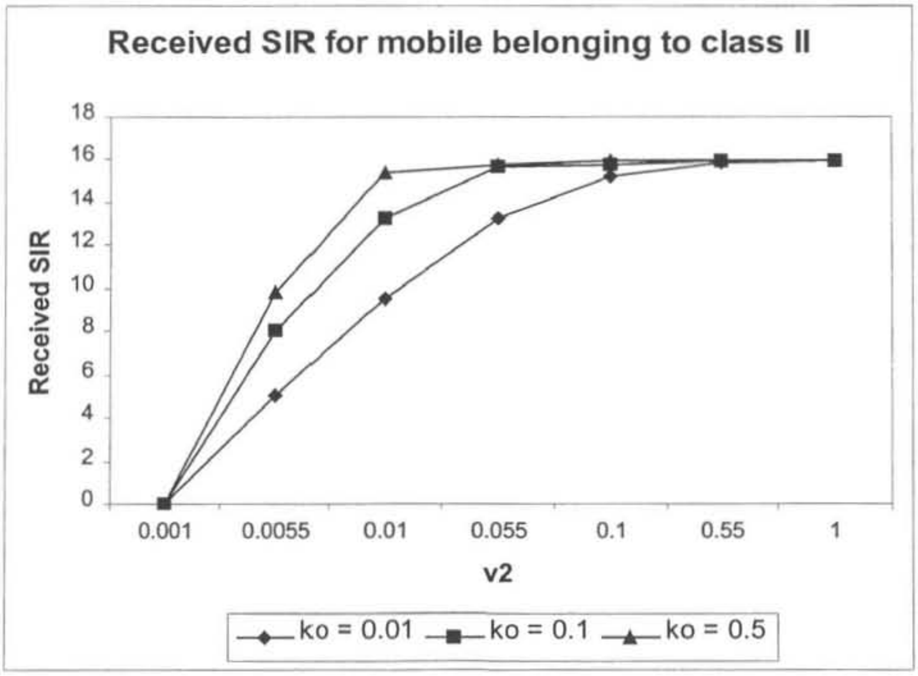

Figure 5-7 Received SIR vs. v_2 for different k_o values (class II)

5.8.2.2 Ripple Magnitude

Figure 5-8 indicates the Ripple Magnitude versus v_2 for different k_o values corresponding to the received SIR from mobile of class II at the base station. Same conclusions with respect to the ripple magnitude for mobile of class II can be drawn, as inferred from the performance graph of mobile of class I (Figure 5-5).

Thus, with k_o set to a high value, a faster convergence is obtained with a slight compromise on the target window.

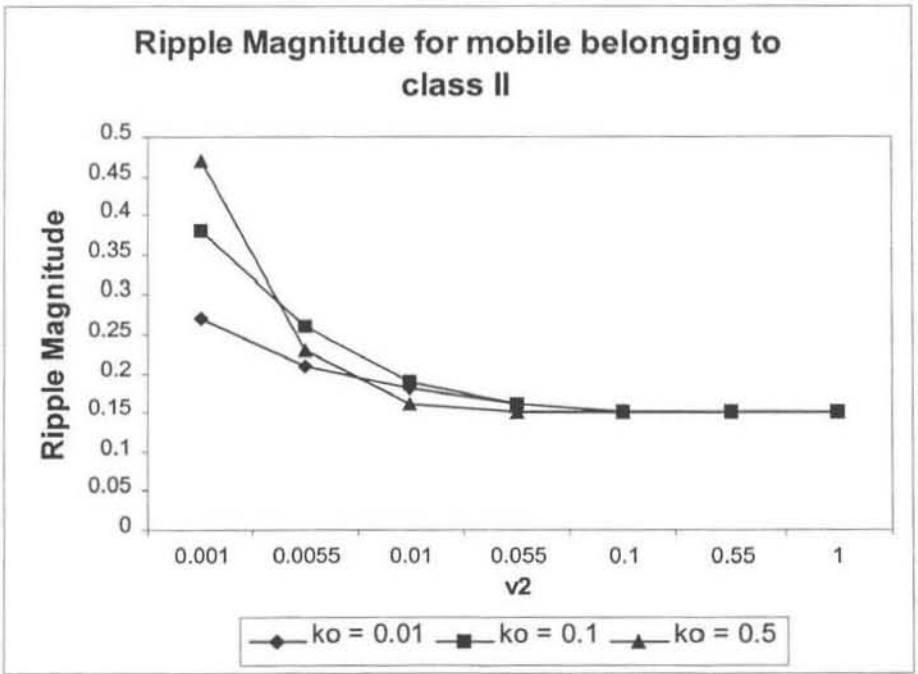

Figure 5-8 Ripple Magnitude vs. v_2 for different k_o values (class II)

5.8.2.3 Delta

Figure 5-9 illustrates the response of step size for different v_2 and k_o values of a mobile belonging to class II. It plays the same role as discussed earlier. Same conclusions can be drawn from the performance graph as obtained from a mobile belonging to class I.

Hence the QoS is successfully delivered to the mobiles belonging to class II with similar response to parameters k_o as experienced by mobiles of class I. Mobiles of classes I and II show satisfactory results as they meet with their respective SIR target levels.

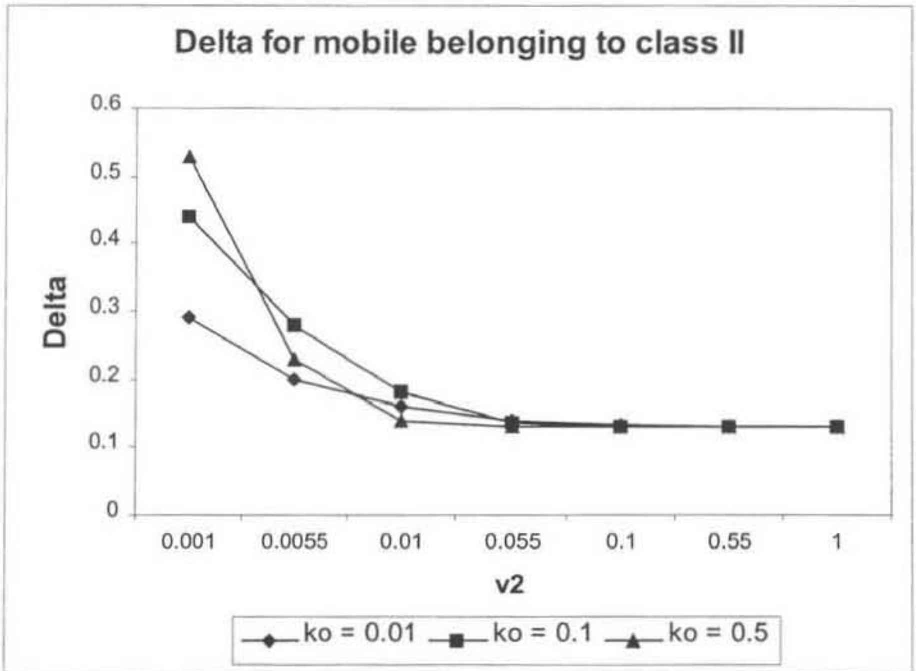

Figure 5-9 Delta vs. v_2 for different k_o values (class II)

5.8.3 Performance results for mobiles of class III

Mobiles belonging to the third class of service produce the following performance results. Mobiles falling in this category of class, demand a very high Quality of Service.

5.8.3.1 Received Signal-to-Interference Ratio

Figure 5-10 illustrates the Signal-to-Interference ratio as received at the base station from a mobile of class III, versus QoS parameter v_3. Results are obtained corresponding to the case where the QoS parameter α_3 is set to a value as high as 5000, reflecting the high QoS demand by the mobiles of class III.

A slightly different conclusion can be drawn from results obtained from mobile of service class III as compared to those obtained from mobiles of both classes I and II. Figure 5-10, indicates that k_o when set to a low value of 0.01, the received SIR at the base station does converge but at a lower level than the required level. However, with high k_o values of both 0.1 and 0.5, the received SIR converges at the desired level, which is α_3/W (79.36) in this case. It is also seen that, with high k_o values, the SIR converges at a higher v_3 value, in contrast with results obtained from classes I and II. This further indicates the high QoS demand required by the mobile users of class III.

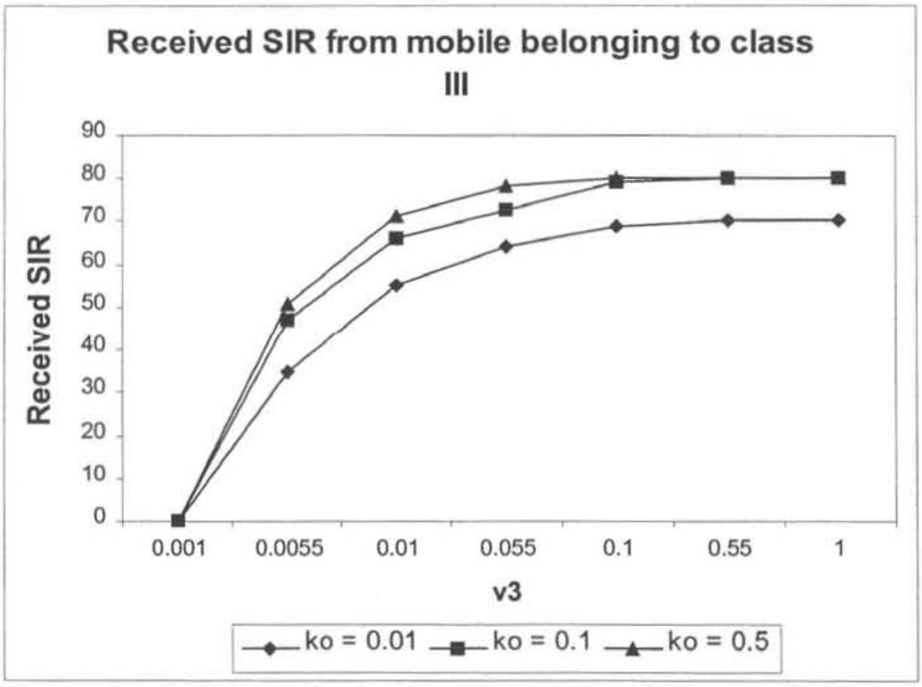

Figure 5-10 Received SIR vs. v_3 for different k_o values (class III)

5.8.3.2 Ripple Magnitude

Figure 5-11 illustrates the Ripple Magnitude for the received SIR versus v_3 for different k_o values. At a low k_o value, the ripple magnitude is small and converges at a lower target window. High k_o values of both 0.1 and 0.5, which help SIR meet the target, have a very high initial ripple magnitude, but later converging to an acceptable window.

Thus, it can be concluded that with a high QoS demand, step size parameter k_o has to be set to a high value, with the trade off that the target window is larger.

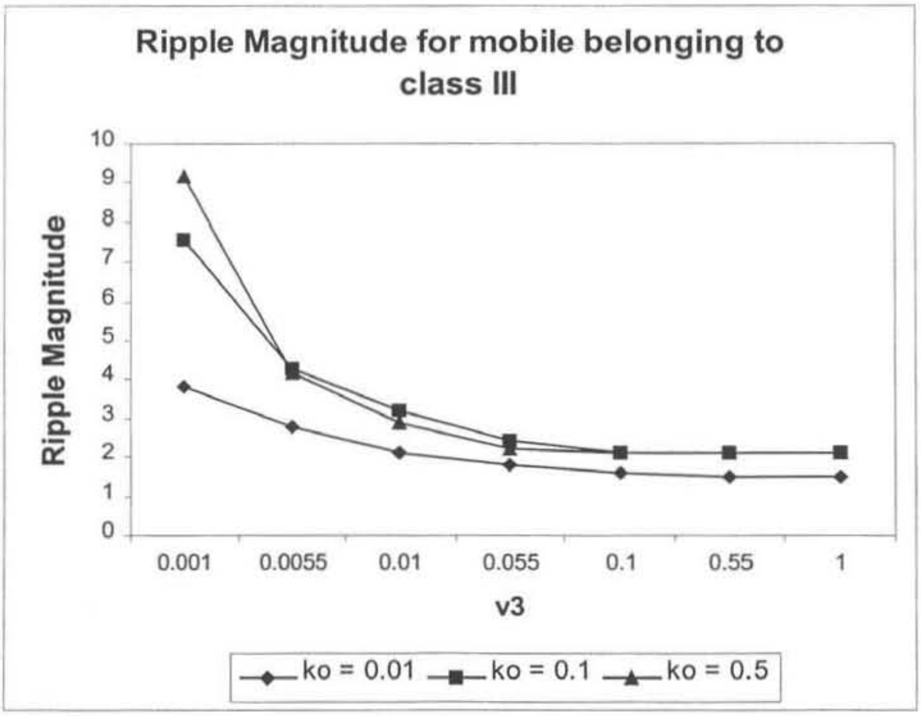

Figure 5-11 Ripple Magnitude vs. v_3 for different k_o values (class III)

5.8.3.3 Delta

The step size adjusts and regulates the transmitted power efficiently as can be seen from Figure 5-12, which illustrates Delta versus v_3 for different k_o values. It can be concluded that even for a very high ripple magnitude corresponding to the case with high k_o value, delta is able to help SIR converge to the required high value.

Mobiles of service class III meet with the high QoS requirements, both in terms of α_3 and v_3.

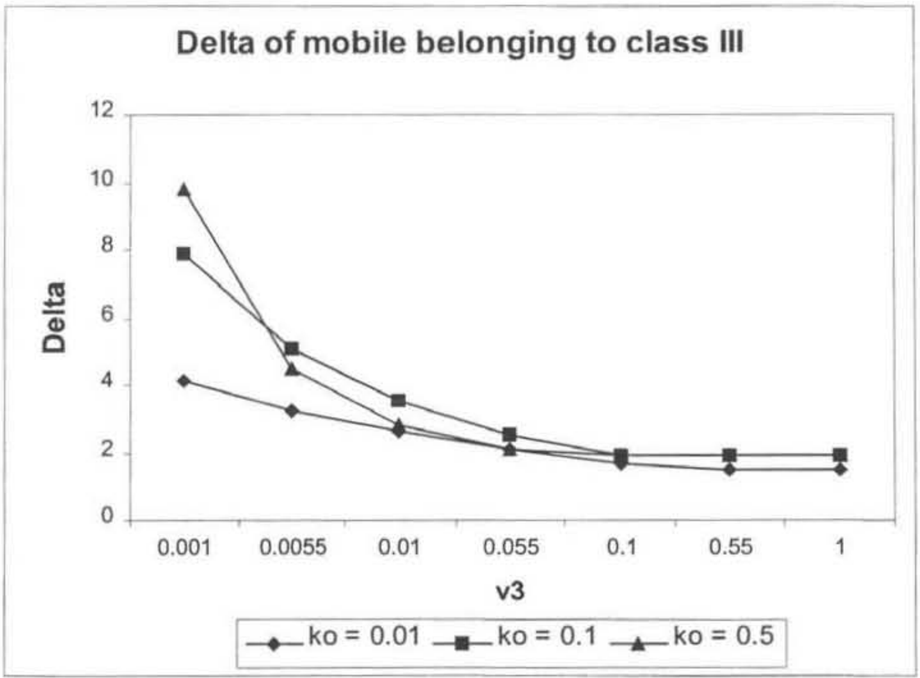

Figure 5-12 Delta vs. v_3 for different k_o values (class III)

5.8.4 Stability Feature Results

Figure 5-13 illustrates a graph of the received power at the base station of a mobile belonging to class I, operating over a period of time. The results obtained clearly indicate that the main aim of controlling the transmitted power of the mobile such that it meets with the desired fixed level and also remains constant at the base station, is achieved.

The same kinds of results were obtained from mobiles belonging to service classes II and III.

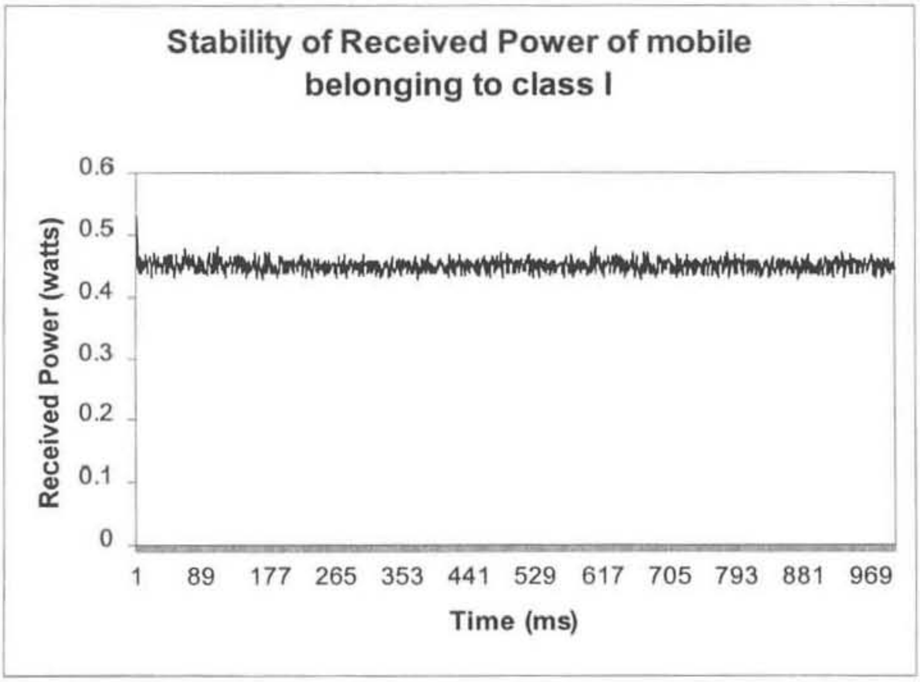

Figure 5-13 Received Power vs. time (class I)

Figure 5-14 shows the received SIR at the base station of a mobile of service class I, as obtained over a period of time. The graph shows that the SIR meets the assigned target after a short initial time span and then remains constant thereafter. The same kinds of results were obtained from mobiles of classes II and III, illustrating the convergence of SIR. They also remain constant at their respective required levels.

These sets of results help us to conclude that the proposed power control and SIR adaptation schemes are stable over a long period of time.

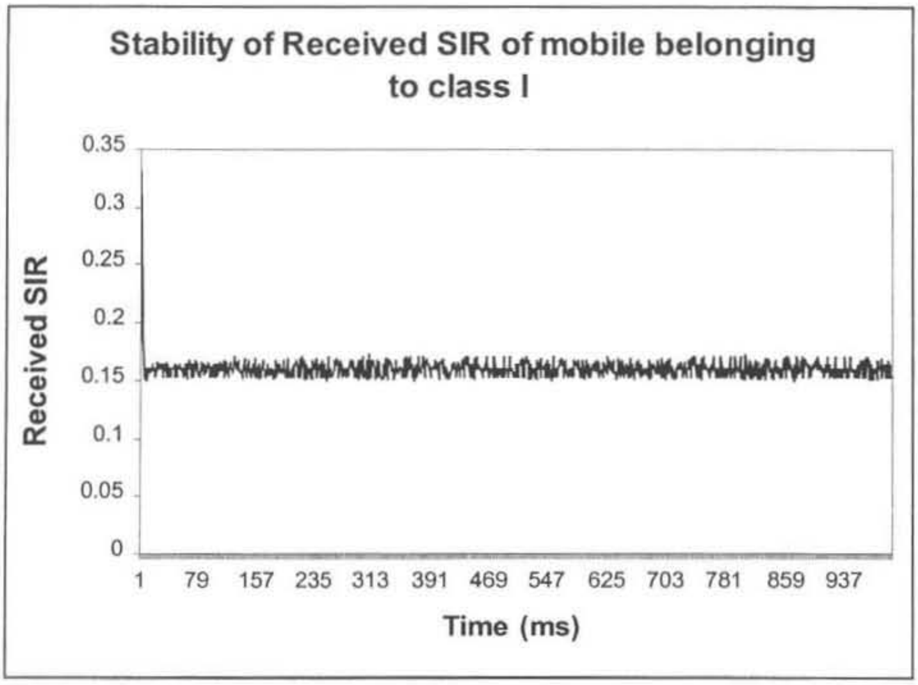

Figure 5-14 Received SIR vs. time (class I)

5.8.5 Comparison with Fixed-Step Power Control Scheme

The graphs in Figure 5-15 are as expected. They depict the received power of a mobile belonging to service class I, when the conventional fixed-step (1dB) power control and the proposed variable-step size power control schemes are implemented in the system. As seen the received power converges at the required level faster when the variable step size power control algorithm is implemented, thereby proving that the proposed power control scheme shows better performance results when compared to those obtained from a fixed-step power control scheme. The same kinds of results were obtained from mobiles belonging to service classes II and III.

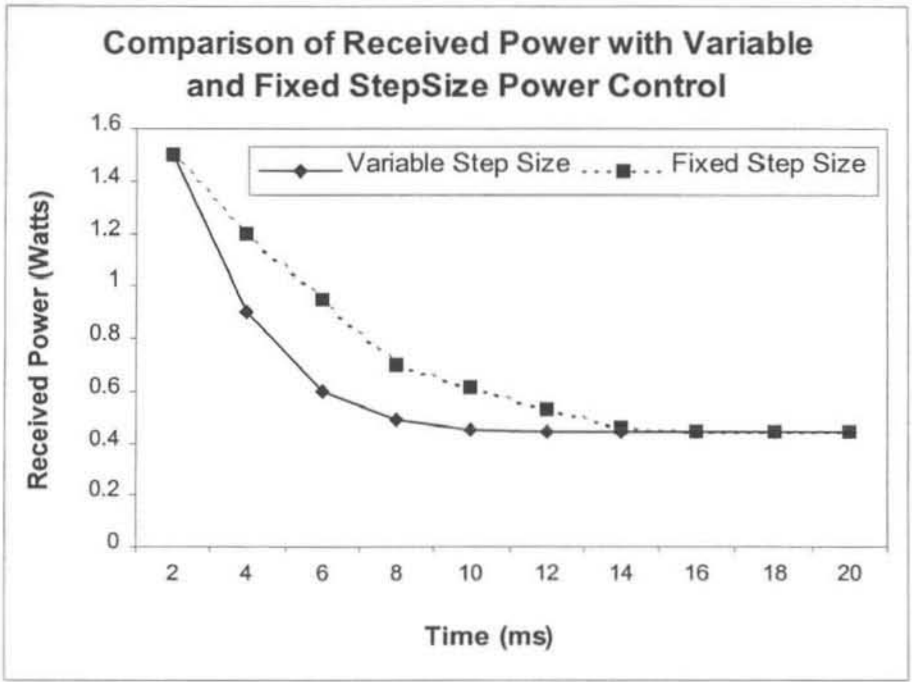

Figure 5-15 Received Power – Fixed and Variable Step Size Power Control

5.9 Summary

Almost all the early works, both in single service and multi-service CDMA systems, have presented power control schemes using a fixed step size power control. The step size is kept constant at 1dB. These algorithms perform nearly as well as the SIR balancing scheme. However in these algorithms, the SIR is kept constant throughout and effects of short-term fading are ignored.

In this chapter, we have derived and investigated the performance of a distributed variable step size power control algorithm in a cellular CDMA network, which supports heterogeneous transmitting sources having diverse characteristics and Quality of Service requirements.

The power control algorithm is a discrete-time feedback adjustment power control scheme. It updates the transmitted power of the mobiles in each of the service classes by a *variable step size* and the only information needed to adjust the transmission power of the mobile terminal is the received SIR at the corresponding base station. The speed, at which power control is performed, depends on the algorithm proposed which designs the step size. This step size is required not only to adjust the transmitted power so as to meet with the QoS, but to follow slow lognormal shadowing, propagation loss as well as mitigate variations caused by fast fading. The variable step size helps in the fast convergence of the SIR to the assigned value and this can also be attributed to the step size constant k_o. Results obtained help us to conclude that higher the value of k_o, faster is the converge of SIR to the desired value.

The SIR adaptation algorithm characterizes the mobiles belonging to different service classes by distinctive QoS parameters, which define the desired minimum SIR level to be satisfied. The two parameters that determine the QoS as demanded by the mobiles of different classes of service are both fixed predetermined quantities. The received power and the SIR for each of the service classes are adapted locally based on the measurements of the mean and variance of the interference caused by the other active mobiles. These factors account for giving the algorithm a more practical approach. Hence, the outer control loop computes the target SIR which on the medium time scale corresponds to the data rate of the user's service and the inner loop assigns transmission powers to track the provided SIR by implementing a variable step size power control while compensating for the channel attenuation.

The results show the fast convergence of the adapted power levels to their optimum levels fulfilling the QoS requirements. It was seen that mobiles belonging to the different classes of service show a similar response with step size parameter k_o. A faster convergence is obtained with a high set value of k_o, with a slight compromise on the target window. Mobiles belonging to the category of service class that requires very high QoS, indicate that k_o has to be set to a high value to be able to achieve the optimum SIR value with the trade off that the target window is slightly larger. Step size efficiently adjusts and regulates the transmitted powers. Variable step size power control in comparison with fixed step size power control, showed better performance by converging at a much faster rate and remaining constant at that level. Both the received SIR and received powers at the base station remain constant at the required level thereby helping us to conclude that the power control scheme proposed is stable.

One of the attractive features of the algorithm is its simplicity. The scheme is insensitive to SIR estimated errors and coordination among the base stations is not required. It is a simple and an effective technique enabling multi-media capabilities into the mobile communication.

CHAPTER 6

EFFECT OF TRUNCATED POWER CONTROL AND QUANTIZATION OF POWER LEVELS

6.1 Introduction

In this Chapter, pragmatic issues like truncation of transmitted power, power level quantization and their effects are addressed and an algorithm derived for each of the above issues. Both truncation of transmitted power and power level quantization are inevitable aspects of power control, which cannot be ignored, in the practical implementation of power control in CDMA systems. We move a step further by incorporating power level quantization and truncated power control in the distributed variable step size power control scheme for multimedia and multi-cellular CDMA systems.

6.2 Truncated Power Control

It is well known that CDMA systems that employ correlation receivers suffer from near-far problem: the problem of a strong signal masking out a weaker signal, causing unreliable detection of the latter. As mentioned in the earlier chapters, the conventional way of maintaining a desired signal strength at the receiver is that each transmitter estimates the channel power gain $G(n)$ at time 'n' and inverts the channel power gain by adjusting the transmit power $P(n)$ as $P(n) = R(n)/G(n)$, where $R(n)$ is the target received signal power. However, this conventional power control scheme requires a large average transmit power to compensate for deep fades. It also exacerbates the interference caused by boundary mobiles to adjacent cells, since they typically must transmit at a very high power to compensate for path loss and shadowing effects. Thus, a truncated power control scheme, which mitigates these undesirable effects, is to be considered.

The motivation for applying truncated power control to a network is as follows:

- Mobiles on the cell boundaries are more likely to have buildings blocking their line-of-sight to the base station and are therefore more likely to experience deep shadowing. The truncated power control is expected to reduce the interference caused by mobiles on cell boundaries, since these mobiles will often be in outage and therefore will not contribute to adjacent channel interference.

- Truncated power control reduces the required average transmit power, since it need not compensate for deep fading.

- Truncated power control provides a power gain over conventional power control for the channel model consisting of Rayleigh fading, lognormal shadow and path loss. The power gain translates into a reduction of the required transmit power for a given performance.

- Truncated power control has been shown to increase the spectral efficiency of non-spread-spectrum single-user systems [Goldsmith & Chua, 1997].

The required transmit power for CDMA systems is often neglected since the system is assumed to be interference limited; thus scaling the average transmit power of all users has no effect, since both the signal and interference power scale accordingly. However, the noise power must also be factored into the performance calculation, and it is seen that when both interference and noise are taken into account, truncated power control reduces the average transmit power required to achieve a given performance. However, this reduction comes at the expense of an increase in the truncation probability, which is defined as the probability that the channel is below the cutoff fade depth γ.

The transmission rate during active i.e., non-truncated conditions, is increased relative to γ such that the data rate averaged over both active and non-active conditions is the same for all γ. Thus, changing the truncation threshold γ does not have an impact on this average data rate, which corresponds to the average rate experienced by a user moving throughout the coverage region.

6.3 Conventional method of truncation – no transmission in case of deep fade.

Kim and Goldsmith [2000] have proposed a truncated power control scheme for a single service CDMA system. They determine the outage probability and power gain of truncated power control applied to both single-cell and multi-cell CDMA systems. With truncated power control, the transmit power is adjusted to compensate for the lognormal shadowing and path loss above a certain cutoff fade depth γ_o. In implementing this technique, the mobile user 'i' estimates the propagation gain G_i associated with slow lognormal shadowing and path loss and adjusts its transmit power $P_i(n)$ such that:

$$P_i(n) = \begin{cases} \dfrac{R_i}{G_i} & \text{if} \quad G_i \geq \gamma_o \\ 0 & \text{if} \quad G_i < \gamma_o \end{cases} \tag{6-1}$$

where R_i is the received signal power when $G_i \geq \gamma_o$ and the value of R_i is adjusted to meet the target bit error probability.

According to the above truncated power control algorithm, the transmitter does not transmit (no service) if the link gain is less than the cutoff fade depth. The active factor, which is the fraction of time during which the mobile transmits ($p(\gamma_o)$), depends on the cutoff fade length γ_o and the received signal power R_i can be controlled either by the transmit power P_i or γ_o. The transmit power can be traded with the activity factor in maintaining a desired received signal power. In the algorithm, in order to maintain a constant average data rate D_s bits/s independent of the activity factor, the bit duration T during $G_i \geq \gamma_o$ must be set to $p(\gamma_o)/D_s$, since the data transmission rate when $G_i < \gamma_o$ is zero. As a result, the processing gain T/T_c, where T_c is the chip duration, changes as $p(\gamma_o)$ is changed. T_c is assumed to be constant in the algorithm.

Thus, truncated power control compensates for fading above a certain cutoff fade depth and increases the data rate during transmissions so that the average data rate is independent of the cutoff depth and its associated activity factor.

The results obtained indicated that the truncated power control scheme is most effective for channels with large power fluctuations. This result is expected since channels with large power fluctuations will experience deep fades more often, and conventional power control schemes use a great deal of power to compensate for these deep fades.

The algorithm when implemented in a multicellular system shows that the truncated power control exhibits a capacity gain of about twenty to eighty percent [Kim & Goldsmith, 2000]. As a truncation probability is increased, a higher power gain and capacity gain is obtained.

At low occupancy rates, i.e., the traffic is low; the outage probability increases as the truncation probability increases. However, at high-occupancy rates, the outage probability decreases as the truncation probability decreases i.e., as the cutoff threshold γ_o is increased. This is because the multiple-access interference (MAI) is reduced by decreasing the activity factor, and the outage probability is dominated by the probability of MAI exceeding the limit.

6.4 Truncated Power Control with Threshold Transmit Power in case of deep fade

In this section, the proposed truncated power control is presented for a multicellular and multimedia CDMA system. We build up on the conventional truncated power control scheme, discussed in the previous section, taking into account and covering up for the limitations that exist in the conventional power control scheme.

The conventional truncated power control scheme considers the use of truncated power control in CDMA systems with slow lognormal shadowing, path loss and Rayleigh fading. However, since fast fading is typically difficult to track, it was seen that only lognormal shadowing and path loss were assumed and not Rayleigh fading. Instead, a RAKE receiver to mitigate the effects of fast fading was used.

Moreover, the conventional truncated power control compensates for fading above a certain cutoff fade depth *only*. In case of deep fades, the mobile user does not transmit power. Practically, this may seem to be impossible.

The above two limitations of the conventional power control scheme, which cannot be ignored from a practically point of view, have been taken care of in the proposed truncated power control scheme.

The same system model, as used in the variable step size power control algorithm, proposed in Chapter 5, is assumed. The link gain $G_{ij}(n)$ is calculated as given in equation (5-8), taking into account the correlated lognormal shadow fading, path loss and correlated Rayleigh fading. Each mobile '*i*' adjusts its transmit power such that:

$$P_{ij}^{*}(n+1) = \begin{cases} P_{ij}(n+1) & \text{if} \quad G_{ij}(n) \geq \gamma_j \\ P_{j(\max)} & \text{if} \quad G_{ij}(n) < \gamma_j \end{cases} \tag{6-2}$$

where $P_{ij}(n+1)$ is the transmit power updated as calculated in the distributed variable step size power control algorithm given in equation (5-22). γ_j is the cutoff fade depth for each of the service classes '*j*' and $P_{j(max)}$ is the threshold or the maximum power that the mobile '*i*' belonging to service class '*j*' is allowed to transmit at. γ_j and $P_{j(max)}$ are both preset values for each of the service classes.

Thus, when the link gain is greater than or equal to the cutoff fade depth, the mobile transmits at the same power level as requested, so as to meet with the desired received power level at the base station. And in case, the link gain is less than the cutoff fade depth, instead of transmitting at a very high power or no power at all, the mobile transmits at the maximum level it has been set to. This compensates for the high loss.

Hence, the transmit power $P_{ij}^{*}(n+1)$ is adjusted to meet with the target SIR defining QoS requirements given the current interference conditions in both the cases – when the link gain is greater than or equal to or when it is less than the cutoff fade depth. Although it may take a few more steps for the received power to converge at the required level, no connection is lost due to lack of transmission power in contrast to the early work.

The main features of the proposed truncated power control scheme with a threshold transmit power are:

- It compensates for the fast Rayleigh fading.
- No connection is lost with the base station at any time instant due to lack of transmitted power, thereby making the proposed truncated power control scheme feasible.
- It gives better performance than the earlier scheme.

- It results in a capacity increase of the system.

6.5 Simulation Model for Truncated Transmit Power Control Schemes

A software simulation of a 25 cells multimedia network including path loss, lognormal fading, Rayleigh fading and variable step size power control is modeled to investigate the performance of truncated power control. The same model as used in Chapter 5 is set up which included the receiver noise η_o. Following the rules of the truncated power algorithm, the link gain at each time '*n*' is calculated and compared to the cutoff fade depth set for that particular service class '*j*'.

The simulation is run for three different cases, enabling us to study the performance results of truncation in depth and with more clarity. Power control without any truncation on transmit power, power control with no transmission in case of very high loss and the proposed power control model when a limit is set on the maximum power that a mobile can transmit at, are modeled. All the three power controls are implemented in a multi-service environment and in case of the latter two cases; the same cutoff fade depth values are used.

6.5.1 Truncated Power Control with no Transmission in case of Low Gain

The truncated power control as derived by Kim & Goldsmith [2000] is implemented in a multi-cellular and multi-service set up. The event-driven software simulator carries out the same events performed by specific subroutines to calculate the link gain $G_{ij}(n)$, which takes into account lognormal shadowing

$A_{ij}(n)$, Rayleigh fading $B_{ij}(n)$ as used in the previous Chapter. The following subroutine for truncated power control is incorporated into the model.

TRUNCATED_POWER_CONTROL Subroutine

....

For each cell

  For each class j

    For each mobile i

      Retrieve link gain $G_{ij}(n)$

      Retrieve cutoff fade depth value γ_j

      Retrieve received power $R_{ij}(n)$

      If

        Link gain $G_{ij}(n) \geq \gamma_j$

        User transmit power $P_{ij}(n) = \dfrac{R_{ij}(n)}{G_{ij}(n)}$

      Else

        User transmit power $P_{ij}(n) = 0$

        Store relevant information

    End for

  End for

End for

6.5.2 Truncated Power Control with Threshold Transmitted Power in case of Low Gain

The same system model is used and the following subroutine, which introduces the proposed truncated power control, that combats deep fading, replaces the conventional truncated power control scheme presented in the previous section 6.5.1.

TRUNCATED_THRESHOLD_POWER_CONTROL Subroutine

For each cell

For each class *j*

For each mobile *i*

Retrieve link gain $G_{ij}(n)$

Retrieve cutoff fade depth value γ_j

Retrieve transmit power $P_{ij}(n+1)$

Retrieve maximum transmit power $P_{j(max)}$

If

Link gain $G_{ij}(n) \geq \gamma_j$

User transmit power $P_{ij}^{*}(n+1) = P_{ij}(n+1)$

Else

User transmit power $P_{ij}^{*}(n+1) = P_{j(max)}$

Store relevant information

End for

End for

End for

6.5.3 Simulation Parameters

The following simulation parameters were used in the simulation along with some relevant ones from Tables 5-1, 5-2 and 5-3.

Cutoff fade depth (*watts*)	Symbol	Value
Class I	γ_1	0.9
Class II	γ_2	1.5
Class III	γ_3	1.7

Table 6-1 Cutoff Fade Depth Model

Maximum Transmit Power (*watts*)	Symbol	Value
Class I	$P_{1(max)}$	0.6
Class II	$P_{2(max)}$	35
Class III	$P_{3(max)}$	65

Table 6-2 Maximum Transmit Power Model

6.6 Results for the Truncated Transmit Power Control Schemes

In this section, the results obtained from the simulation are presented. The speed, at which the powers of the mobile users are regulated and controlled, depends largely on the proposed algorithm which combats the deep fades by truncated transmitted powers. It also depends on the step size designed by the distributed variable step size algorithm, which follows the channel variations closely. Performance results are obtained and studied for the cases where a mobile belonging to a class of service experiences no truncation and in another case where the transmitted powers are restricted, following the rules of the conventional and the proposed schemes separately. The results obtained from all the three different cases are compared. The step size constant k_o is set to a value of 0.1 for all the classes of service, as a high k_o value is a prerequisite for mobiles of class III which have a high QoS demand.

6.6.1 Performance results without truncation, with conventional and proposed truncation schemes for mobile of class I

Figure 6-1 illustrates the probability of the power as received at the base station from mobile of class I. Results obtained from all the three cases are presented together in the graph to enable us to compare with ease, the results obtained.

The results show that the received power without truncation is 0.45 watts i.e., the mean of the received power, has the highest occurrence with a probability of 56%. The received power with the conventional truncation power control scheme is 0.45 watts with a highest occurrence of a probability of 61% and that with the proposed scheme is 67%. In the proposed scheme, the maximum power that the mobile is allowed to transmit at is set to a value of 0.6 watts with a cut off fade depth value of 0.9 and lower. Therefore, in all the three cases the mean of the received power is the same at 0.45 watts though with different probabilities of occurrence.

The amount by which the received power varies about its mean is also seen to be different in the three cases. We see that when the mobile is allowed to transmit at any power the variance is high, resulting in a large ripple magnitude (target range) of the received power. However, it reduces when the transmitted powers are restricted.

The proposed scheme is shown to have better performance results than both the conventional power truncated scheme and the scheme without truncation. The probability of the received power to be at the optimum level is high with a low variance about its mean.

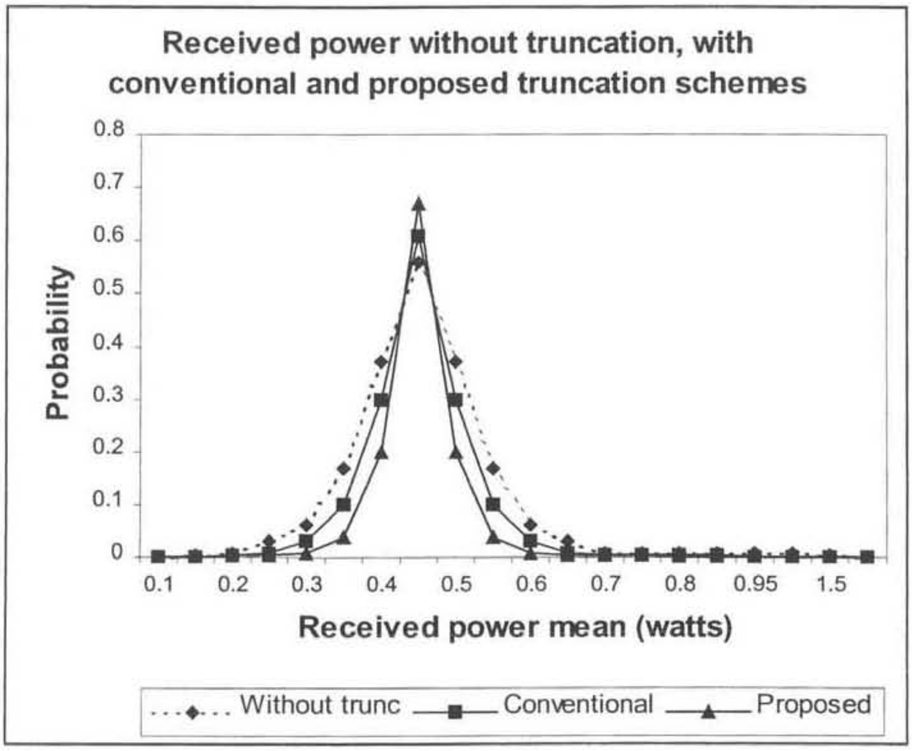

Figure 6-1 Received powers without truncation, with conventional and proposed truncation schemes (class I)

6.6.2 Performance results without truncation, with conventional and proposed truncation schemes for mobile of class II

Figure 6-2 illustrates the probability of the received power at the base station from a mobile belonging to service class II. Simulation results obtained from each of the three cases are compared. The maximum power that the mobile can transmit at is set to 35 watts for a cutoff fade depth value of 1.5 and lower in the proposed truncated power control scheme.

Similar response in terms of the mean of the received power of mobile of class II is obtained as from mobile of class I. The results show that the received power without truncation is 33 watts having the highest occurrence with a probability of 58%. The received power with the conventional truncation power control scheme is also 33 watts with a probability of 64% of occurrence and that with the proposed truncation scheme is the highest at 68%.

The amount the received power varies about its mean is the highest in non-truncated scheme. The tail end as obtained in the result shows that it comparatively takes a bit longer to converge to the optimum value. The variance is the lowest in case of the proposed scheme indicating a low ripple magnitude.

Thus, mobiles of service class II also show a better performance when the transmitted powers have a threshold preset value. Instead of transmitting at very high powers in case of high loss and thereby resulting in an increase in the total interference caused to the other active mobiles, and to the whole system as such, the powers are controlled and regulated without losing any connection.

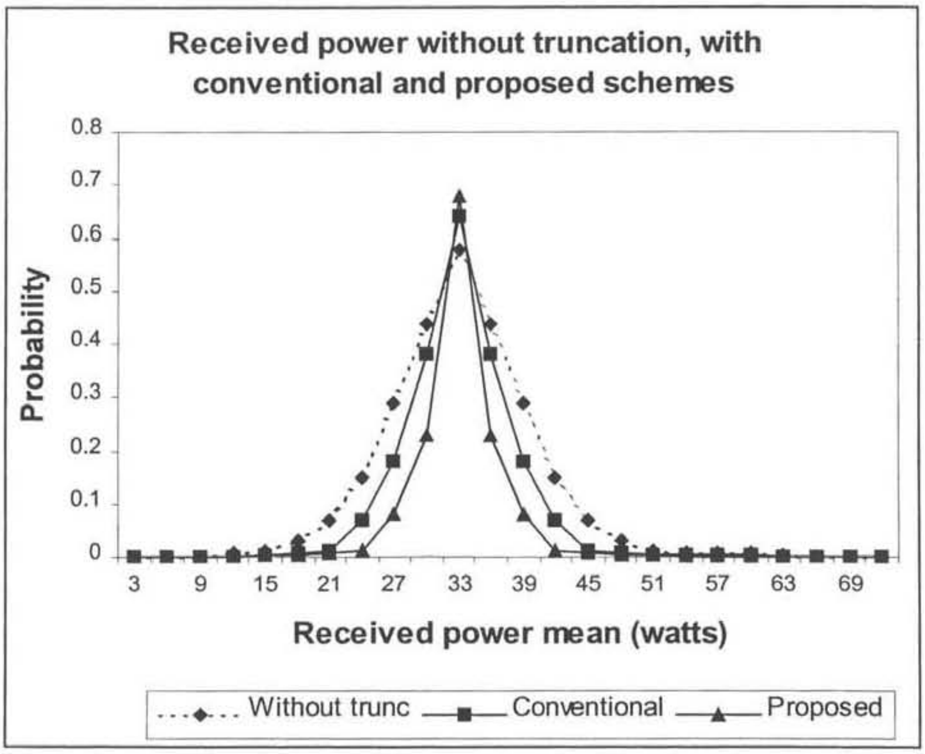

Figure 6-2 Received power without truncation, with conventional and proposed truncation schemes (class II)

6.6.3 Performance results without truncation, with conventional and proposed truncation schemes for mobile of class III

Probability of the power received at the base station from mobile with very high QoS demands categorized in service class III is illustrated in Figure 6-3. In the proposed truncated power control scheme, the maximum power that the mobile can transmit at is set to 65 watts for a cutoff fade depth of 1.7 and lower.

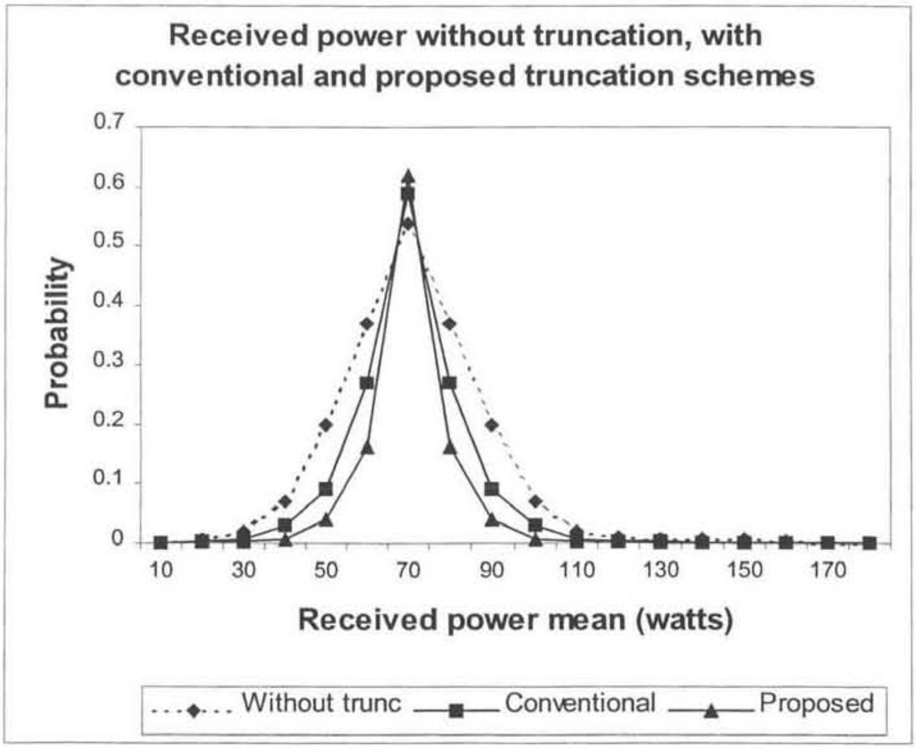

Figure 6-3 Received power without truncation, with conventional and proposed truncation schemes (class III)

Similar response in terms of both the mean and the variance of the received power is obtained from mobile of service class III. The received power has the highest occurrence at the optimum level of 73 watts with different probability of occurrence at 54% in case of no truncation; 59% in case of the conventional method and the highest in case of the proposed scheme at 62%. Hence, better performance results are obtained for the proposed truncated scheme for mobiles belonging to all the three classes of service in the CDMA system. The probability of the received power to be at the required level is higher with a low ripple magnitude. The absence of the tail end in the graphs obtained for the proposed scheme indicates the fast convergence of the scheme.

6.6.4 Stability of proposed truncated power control scheme

Figure 6-4 illustrates the received power of mobile of class I without truncation and with the proposed scheme as obtained over the initial simulation run. The transient state of the signal shows that the truncated scheme not only converges to the optimum level faster but also has a lower target window about the optimum level as compared to the received power without truncation. The received power has a higher ripple magnitude in case the transmission is not truncated which makes us to conclude that the target window is larger.

Figure 6-5 shows the received power after simulations are run over a long period of time. The steady state of the power signal shows that the received power remains constant and has a low ripple magnitude in case the proposed power control scheme is implemented. The received signal without transmitted power truncation converges over a larger target window. Thus, both the schemes are stable, though with different degrees of stability. Truncation results in an increase in the capacity of the system.

The same kinds of results are obtained from mobiles of class II (Figure 6-6a, b) and class III (Figure 6-7a, b).

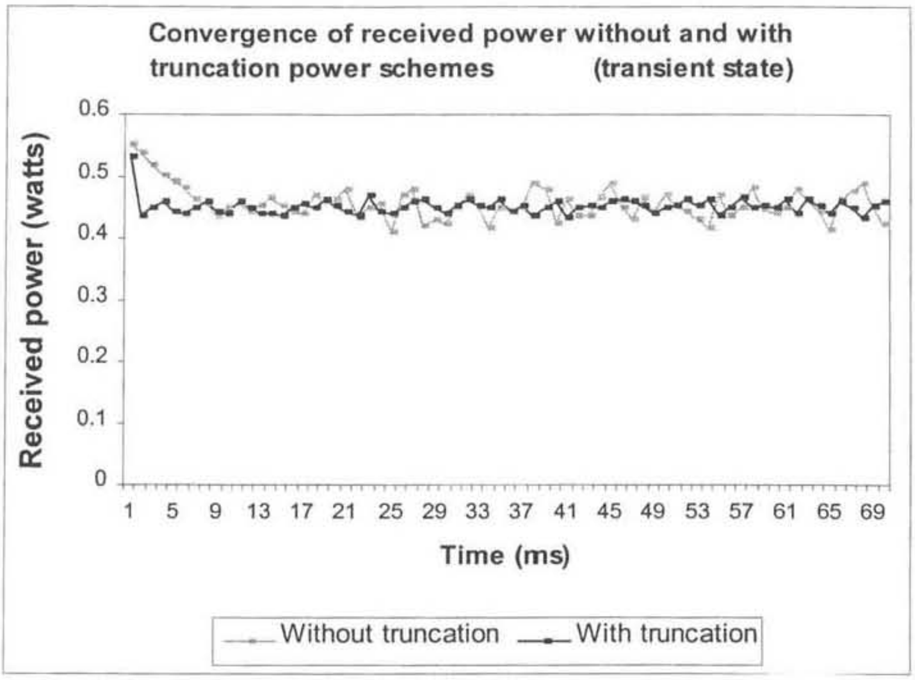

Figure 6-4 Convergence of received power without and with truncation power schemes (class I) – transient state

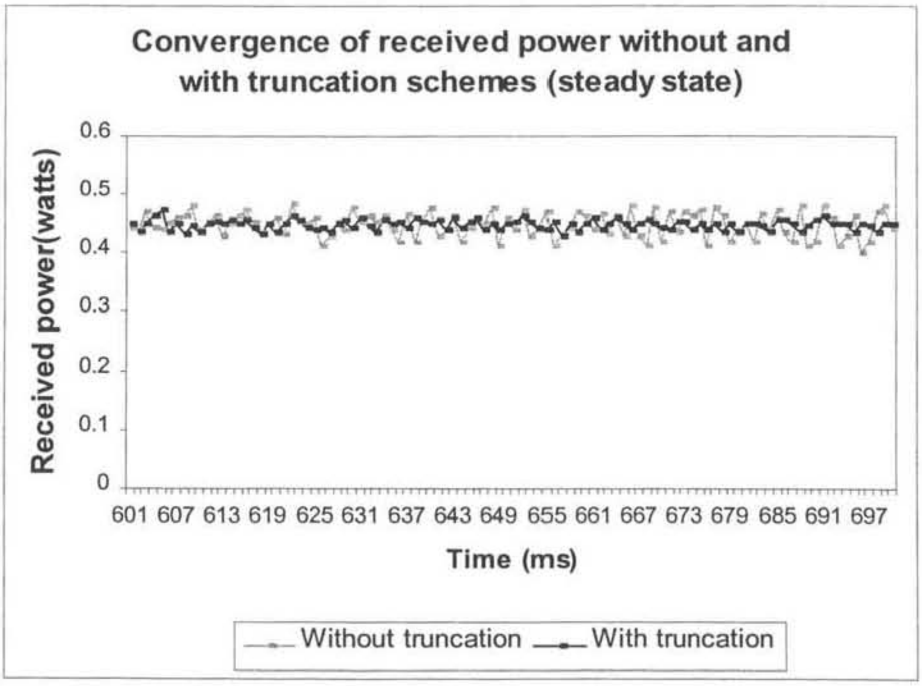

Figure 6-5 Convergence of received power without and with truncation power schemes (class I)– steady state

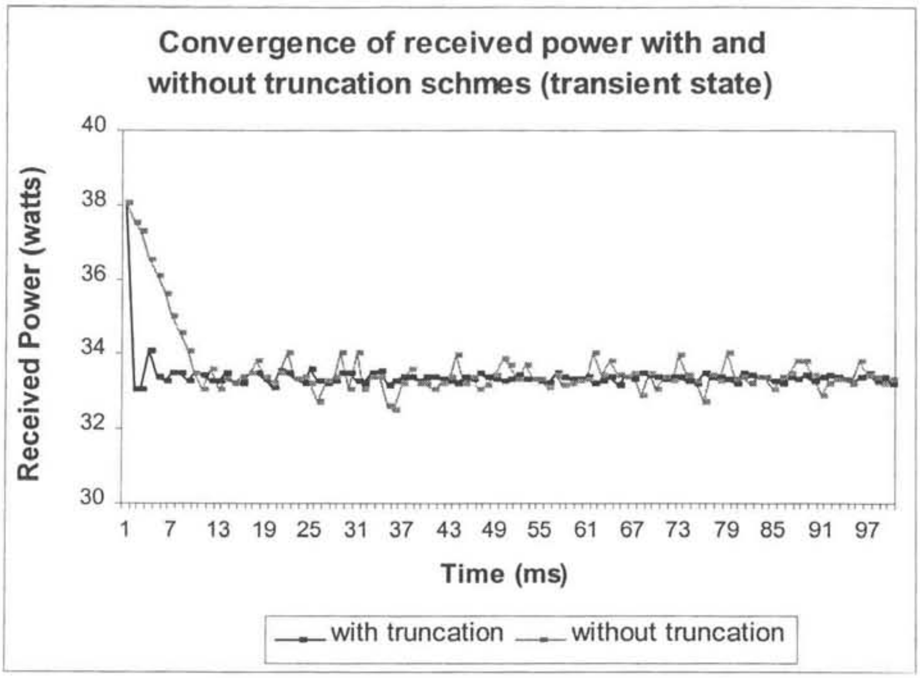

Figure 6-6a Convergence of received power without and with truncation power schemes (class II) – transient state

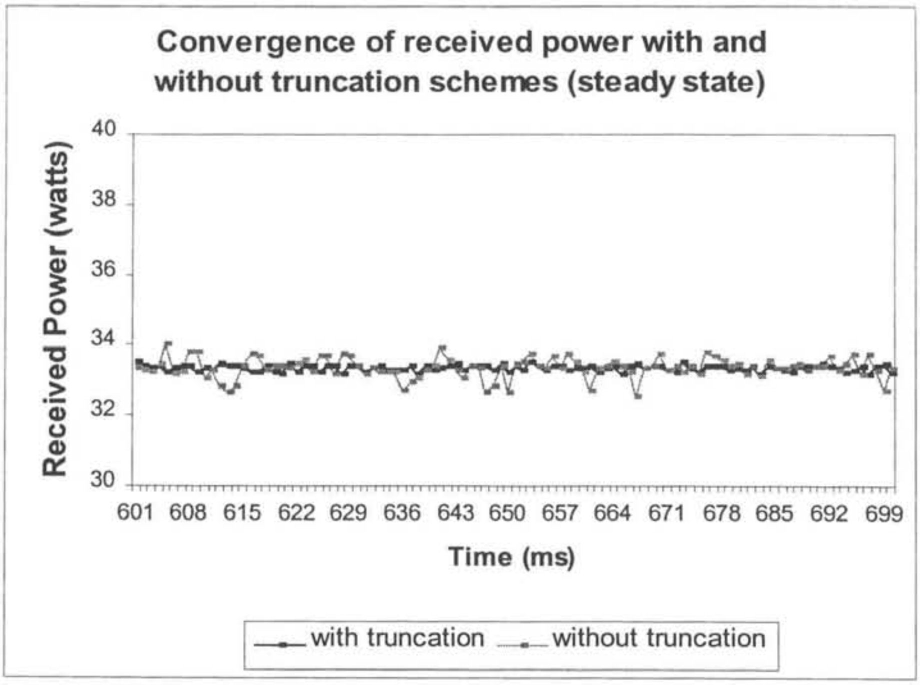

Figure 6-6b Convergence of received power without and with truncation power schemes (class II) – steady state

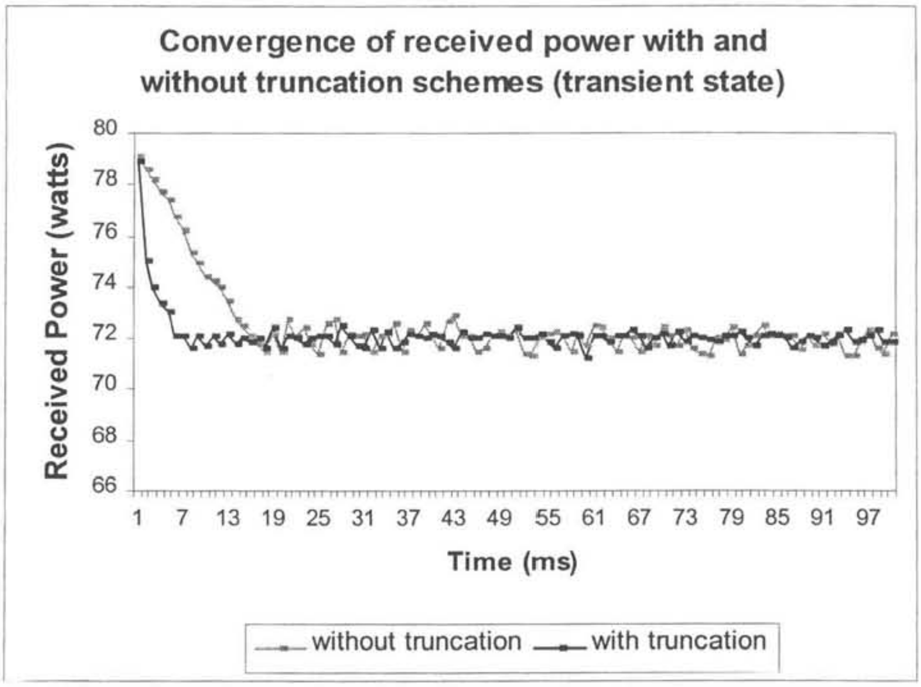

Figure 6-7a Convergence of received power without and with truncation power schemes (class III) – transient state

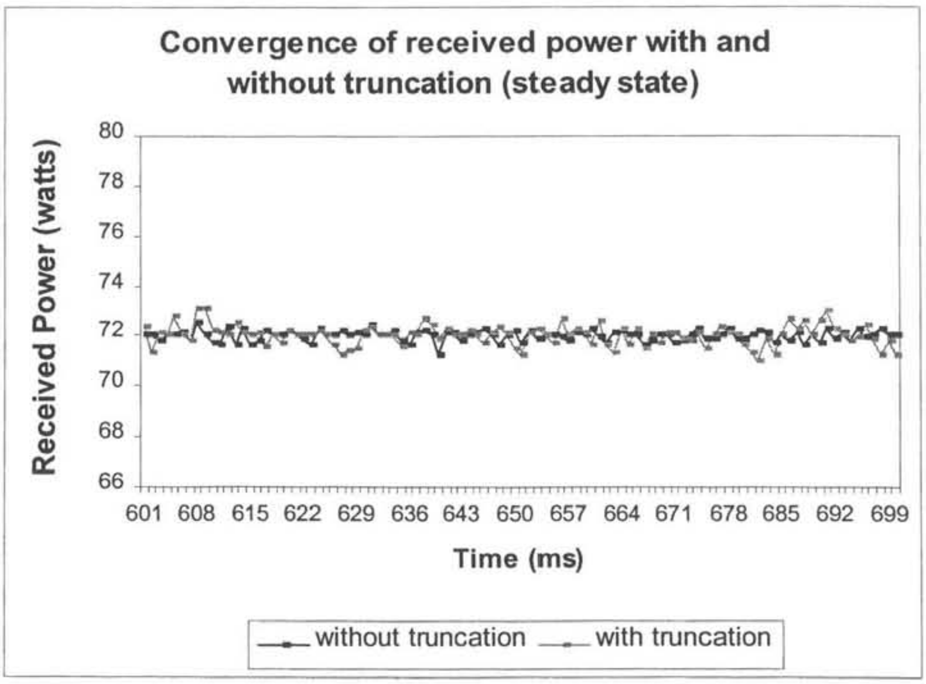

Figure 6-7b Convergence of received power without and with truncation power schemes (class III) – steady state

6.7 Quantization of Power Level

In practical systems, the transmitter power outputs are usually quantized into discrete levels. Lin, Lin, Lee & Su [1995] studied the effect of quantization by simulations. It is shown that for a protection ratio smaller than 20 dB, 32 levels are needed when the power range is 30 dB.

In [Foschini and Miljanic, 1993], [Zander, 1992a] and [Zander, 1992b], the transmission power level can take on any positive real values. In practice, however, some restrictions are inevitable. For example, the power level used cannot be infinitely large [Grandhi & Zander, 1994].

6.7.1 Quantization Power Level in case of a Fixed Step Power Control

In case of a fixed step power control, the quantization level algorithm is quite simple and straightforward. The power levels are assumed to be quantized in logarithmic scale. The difference between two consecutive power levels is represented as $x^{(dB)}$ (>0) dB. Given the power vector $\mathbf{P}_i^*$ for mobile 'i', there exists one and only one quantized power level $\hat{P}_i$, such that:

$$x^{-1/2}\mathbf{P}_{\mathrm{i}}^* \le \hat{P}_i < x^{1/2}\mathbf{P}_{\mathrm{i}}^* \qquad \textbf{(6-3)}$$

If $\hat{\mathbf{P}}$ is the quantized power vector corresponding to the given vector $\mathbf{P}^*$, then:

$$\Gamma_i(\hat{\mathbf{P}}) = \frac{G_i \hat{P}_i}{\sum_{m \neq i}^{I} G_m \hat{P}_m + \eta_o}$$

$$\geq \frac{G_i x^{-1/2} \mathbf{P}^*}{\sum_{m \neq i}^{I} G_m x^{-1/2} \mathbf{P}_m^* + \eta_o}$$

$$\geq x^{-1} \Gamma_i (\mathbf{P}^*)$$

$$= x^{-1} r_i \qquad \textbf{(6-4)}$$

where Γ_i is the Signal-to-Interference ratio of mobile '*i*', and r_i is the protection ratio of mobile '*i*', i.e., if Γ_i is greater than or equal to a prespecified value r_i, the link is considered to be active. The upper bound can similarly be derived as xr_i. Hence the quantized power vector $\hat{\mathbf{P}}$ can be given as [Sung & Wong, 1999a]:

$$x^{-1} r_i \leq \Gamma_i (\hat{\mathbf{P}}) \leq x r_i \qquad \textbf{(6-5)}$$

In a quantized power level system, one can specify a target range with width *2x* dB for each user. If it is possible to find an unconstrained power vector such that the resulting SIR for each user is equal to the mid value of this specified range, then there exists a quantized power vector such that all the individual SIRs fall within the corresponding range.

However, another implication of power level quantization is that it reduces system capacity. For example, when an unconstrained system with a given link gain matrix **G** is considered, there exists power vector **P** such that the SIR value Γ_i is greater than or equal to the protection ratio r_i ($\Gamma_i \geq r_i$) for all the mobiles '*i*'. In a quantized power level system with the same link gain matrix **G**, one can only guarantee that there exists a quantized power vector $\hat{\mathbf{P}}$ such that the SIR Γ_i is greater than or equal to $x^{-1} r_i$. It is possible to construct examples in which some users cannot be accommodated in the quantized system. In other words, the system capacity is reduced. Although the amount of capacity reduction is difficult to quantify, it is clear that larger quantization levels will result in larger reduction in the capacity.

6.7.2 Power level Quantization for Variable Step Size Power Control

In this section the proposed schemes for power level quantization for the variable step size power control algorithm for a multimedia and multi-cellular CDMA system are presented. As discussed and derived in Chapter 5, the power of a mobile '*i*' of class '*j*' is updated to meet with the desired required level at the base station, by a variable step size which is related to both the mean and the variance of the interference caused by all the other active mobiles in the network. One bit quantization level is used.

The step size by which the transmitted power of mobile '*i*' belonging to service class '*j*' is adjusted to meet with the required SIR and received power level is calculated at the base station as given in equation (5-23), i.e.,

$$\delta_{ij}^{T}(n) = \delta_{ij}^{*} + k_{o}\left(\frac{\sqrt{V_{ij}(n)}}{I_{ij}(n)}\right) \qquad \textbf{(6-6)}$$

The transmit power levels are quantized following the rules laid by the variable step size quantized power control scheme:

$$\delta_{ij}^{R}(n) = \begin{cases} +\Delta_{o} & \text{if} \quad \delta_{ij}^{T}(n) > \delta_{ij}^{T}(n-1) \\ -\Delta_{o} & \text{if} \quad \delta_{ij}^{T}(n) < \delta_{ij}^{T}(n-1) \end{cases} \qquad \textbf{(6-7)}$$

where Δ_o takes up a small *constant* value.

Thus, when the step size at time '*n*' at the base station is greater than the step size calculated at time instant '*n-1*', *bit* '**1**' is sent to the mobile station indicating that the step size used for the calculation of transmit power at the mobile station, given by equation (5-22) is to be quantized to a level *increased* by Δ_o. Whereas, if the step size at time '*n*' is less than the step size value at time instant '*n-1*', *bit* '**0**' is sent by the base station which instructs the mobile that the step size for transmit power calculation is to take up a value *decreased* by Δ_o.

We move a step further by extending the derivation of the expression for the quantization of the power level in the variable step size power control scheme. The constant Δ_o is made dependent on time instant '*n*'. Hence, the power levels can be quantized by time dependent variable level as follows:

$$\delta_{ij}^{R}(n) = \begin{cases} +\dfrac{\Delta_o}{2^n - 1} & \text{if} \quad \delta_{ij}^{T}(n) > \delta_{ij}^{T}(n-1) \\ -\dfrac{\Delta_o}{2^n - 1} & \text{if} \quad \delta_{ij}^{T}(n) < \delta_{ij}^{T}(n-1) \end{cases} \qquad \textbf{(6-8)}$$

The step size calculated at the base station at time '*n*' is compared to the step size at time '*n-1*'. If the step size at time '*n*' is greater than the step size calculated at time '*n-1*', *bit* '**1**' is sent indicating that the step size for transmit power is to take up a discrete value increased by $\frac{\Delta_o}{2^n - 1}$. Whereas, if it the step size is less, *bit* '**0**' is sent indicating that the step size for transmit power is to be quantized at a level decreased by $\frac{\Delta_o}{2^n - 1}$.

Thus, in case of a variable step size power control, the power levels can be quantized either by a fixed quantity (Δ_o) or by a variable quantity $\left(\frac{\Delta_o}{2^n - 1}\right)$

6.8 Simulation Model for Quantization Power Level Schemes

The same system model as in variable step size power control scheme in Chapter 5 is modeled, to investigate the performance of the effect of quantization of power levels on the multimedia CDMA system.

The main aim is to quantize the transmit power levels of all the mobiles. Following the rules of the variable step size power control quantization algorithm, the step size at time '*n*' is compared to the value of step size calculated at time '*n-1*' and the transmit power level is quantized taking up a higher or a lower value accordingly.

The simulations are run for three different cases in order to study the effect of quantization for all the classes of service. The received power is monitored both when power levels are quantized by either fixed level or variable levels, and in the other case when power levels are allowed to take any positive real value. The results obtained from both the cases are then compared. The simulations are run for a long time so as to show that the power level can still be kept in a finite range.

6.8.1 Variable Step Size Power Control with Quantization of Power Levels by a Fixed Level

Simulations are run with inclusion of the following deterministic subroutine for quantization of power levels by a fixed level, into the simulation model structured for multicellular and multiservice distributed variable step size power control in CDMA network as in Chapter 5. The software simulator follows the same set of events performed by specific subroutines to produce the results.

FIXED_QUANTIZED_POWER CONTROL Subroutine

For each cell

For each class *j*

For each mobile *i*

Retrieve base_station_transmit step size at '*n*', $\delta_{ij}^{T}(n)$ from tables

Retrieve base_station_transmit step size at '*n-1*', $\delta_{ij}^{T}(n-1)$

Retrieve constant Δ_o from initialization subroutine

If

Base_station_transmit step size

$\delta_{ij}^{T}(n) > \delta_{ij}^{T}(n-1)$

Mobile_station_received step size $\delta_{ij}^{R}(n) = +\Delta_0$

Else

Mobile_station_received step size $\delta_{ij}^{R}(n) = -\Delta_0$

Store relevant information

End for

End for

End for

6.8.2 Variable Step Size Power Control with Quantization of Power Levels by a Variable Level

Simulations are run with the inclusion of the following deterministic subroutine for quantization into the already existing main model.

VARIABLE_QUANTIZED_POWER_CONTROL Subroutine

For each cell

For each class *j*

For each mobile *i*

Retrieve base_station_transmit step size at '*n*', $\delta_{ij}^{T}(n)$ from tables

Retrieve base_station_transmit step size at '*n-1*', $\delta_{ij}^{T}(n-1)$

Retrieve constant Δ_o from initialization subroutine

If

Base_station_transmit step size $\delta_{ij}^{T}(n) > \delta_{ij}^{T}(n-1)$

Mobile_station_received step size $\delta_{ij}^{R}(n) = +\frac{\Delta_o}{2^n - 1}$

Else

Mobile_station_received step size $\delta_{ij}^{R}(n) =$

$$-\frac{\Delta_o}{2^n - 1}$$

Store relevant information

End for

End for

End for

6.8.3 Simulation Parameters

The following simulation parameters were used in the simulation in addition to the Network layout parameters, Network model parameters and the Fading model parameters given in Tables 5-1, 5-2, and 5-3 respectively.

Item	Symbol	Value
Step Size constant for all the three classes of service	k_o	0.1
Quantization level constant	Δ_o	0.01

Table 6-3 Quantization Power Level Model

6.9 Results for Quantization Power Level Schemes

Simulation results obtained for the quantization are presented in this section, which enable us to study the effect of quantization of power levels on the system. Performance and convergence results are obtained, studied and compared for all the three mentioned cases. The step size constant k_o is set to 0.1 for all the classes of service.

6.9.1 Performance results without quantization, with fixed level quantization and variable level quantization for mobile of class I

Figure 6-8 illustrates the probability of the power as received at the base station from mobile of class I.

The results show that the received power without quantization is 0.45 watts with a highest occurrence of a probability of 63%. The received power with variable level quantization has the highest occurrence of a probability of 57%. And the received power with fixed level quantization shows a probability of 51%. From the graph obtained, it can be seen that in all the three cases the mean of the received power is the same at 0.45 watts, though with varying probabilities of occurrence.

The amount by which the received power varies about its required value is seen to be different in the three cases. It is seen that when the power levels are quantized by a fixed level, it results in a larger ripple magnitude of the received power, reflecting that the received power converges to a larger target window.

The system shows better results in case the power levels are allowed to take any value. Amongst the two proposed quantized schemes, the scheme which allows the power level to be quantized by variable levels shows better performance as the probability of the received power to be at the required level is high with a low variance about its mean.

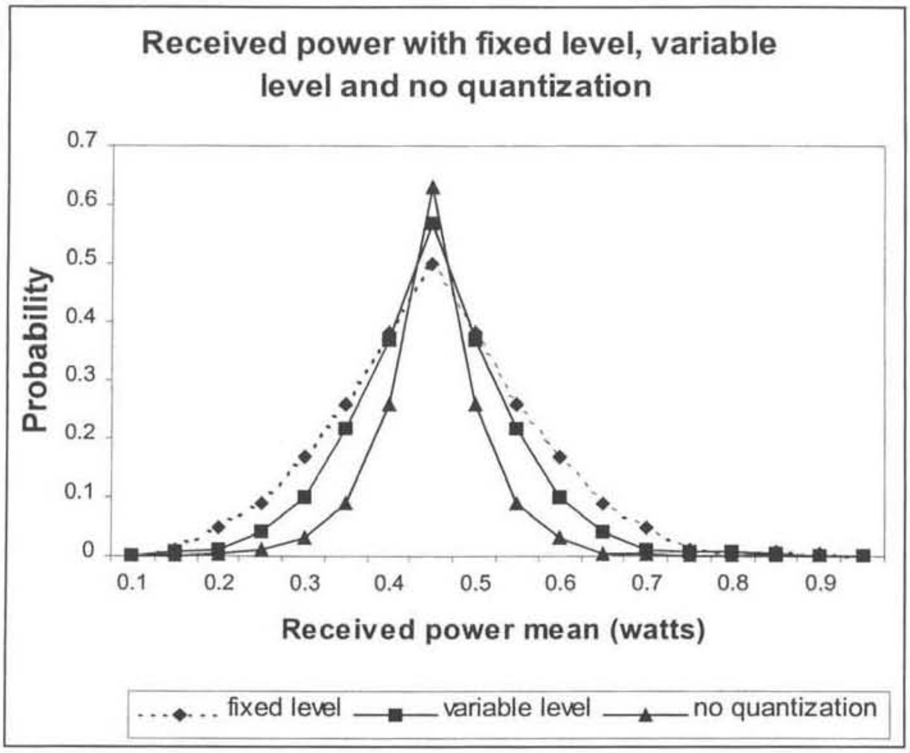

Figure 6-8 Received power without quantization, with fixed level quantization and variable level quantization for mobile of class I.

6.9.2 Performance results without quantization, with fixed level quantization and variable level quantization for mobile of class II

Figure 6-9 illustrates the probability of the received power at the base station from a mobile belonging to service class II. Simulation results obtained from each of the three cases are compared.

Similar response in terms of the mean of the received power of the mobile of class II is obtained as from mobile of class I. The results show that the received power without quantization is 33 watts having the highest occurrence with a probability of 61%. The received power with the variable level quantization power control scheme is also at 33 watts with a probability of 55% of occurrence and that with the fixed level quantization variable step size power control scheme is at 51%.

The amount by which the received power varies about its mean is the highest in case the power levels are quantized by Δ_o. The variance is the lowest in case of the non-quantized scheme indicating a low ripple magnitude.

Thus, the mobile of service class II also shows a better performance when the power levels are not quantized. However, power levels when quantized by $\frac{\Delta_o}{2^n - 1}$ show better results than when quantized by Δ_o.

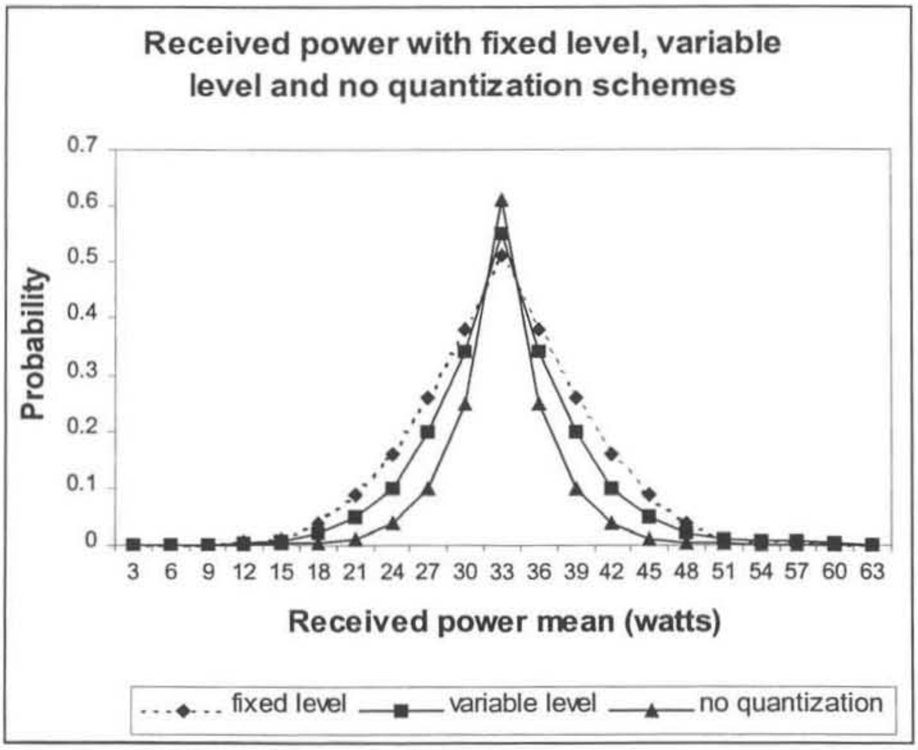

Figure 6-9 Received power without quantization, with fixed level quantization and variable level quantization for mobile of class II

6.9.3 Performance results without quantization, with fixed level quantization and variable level quantization for mobile of class III

Probability of power received at the base station from mobile of service class III is illustrated in Figure 6-10.

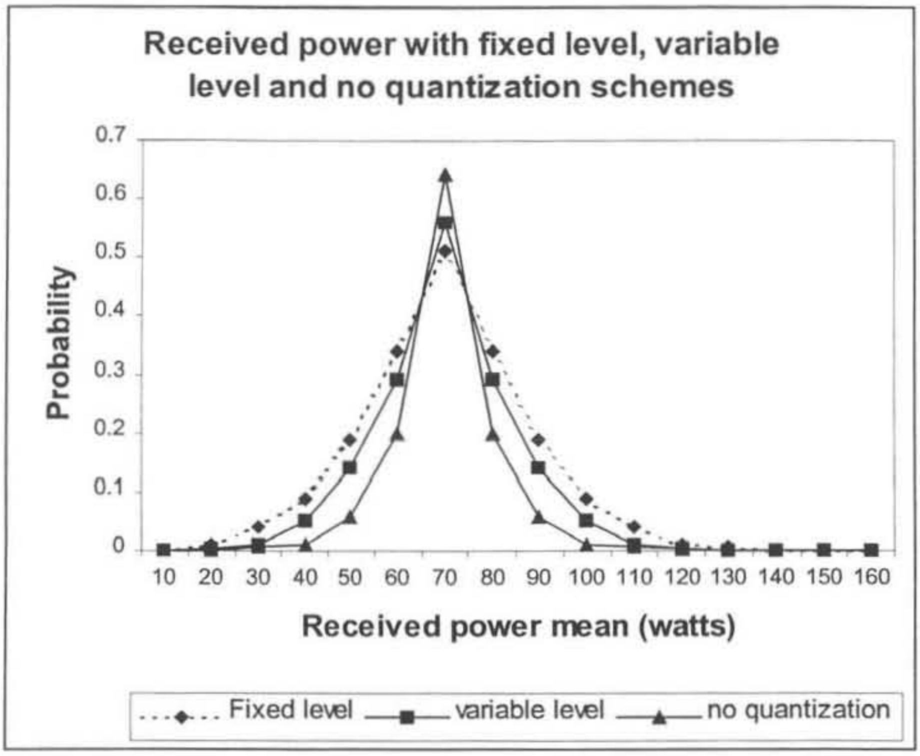

Figure 6-10 Received power without quantization, with fixed level quantization and variable level quantization for mobile of class III

Similar response in terms of both the mean and the variance of the received power is obtained. The received power has the highest occurrence at the required level of 73 watts with different probabilities of occurrence at 64% in case of no-quantization, 56% in case of quantization by $\frac{\Delta_o}{2^n - 1}$ and 51% in case the power levels are quantized by Δ_0. The ripple magnitude is seen to be the highest in case the power levels are quantized by Δ_o.

Hence, better performance results are obtained in case the power levels are quantized by $\frac{\Delta_o}{2^n - 1}$ than by Δ_o for all the three classes of service. The received power converges within a lower target window and with a higher probability that the received power is at the required level.

6.9.4 Convergence of received power with and without quantization

Figure 6-11 illustrates the received power of mobile of class I as obtained during the initial simulation run when the power levels are not quantized and in another case when the power levels are quantized by $\frac{\Delta_o}{2^n - 1}$. The transient state of the signal shows that the quantized scheme not only converges to the optimum level slower but also has a larger target window about the optimum level as compared to the received power without quantization. This results in a decrease of the total capacity of the system.

Figure 6-12 shows the received power after simulations are run for a long period of time. The steady state of the power signal shows that the received power has low ripple magnitude when the power levels are not quantized. However, both the schemes i.e., when the power levels are quantized by $\frac{\Delta_o}{2^n - 1}$ and when the power levels are allowed to take any positive value, are stable though with different degrees of stability. The same kinds of results are obtained from mobiles of classes II and III.

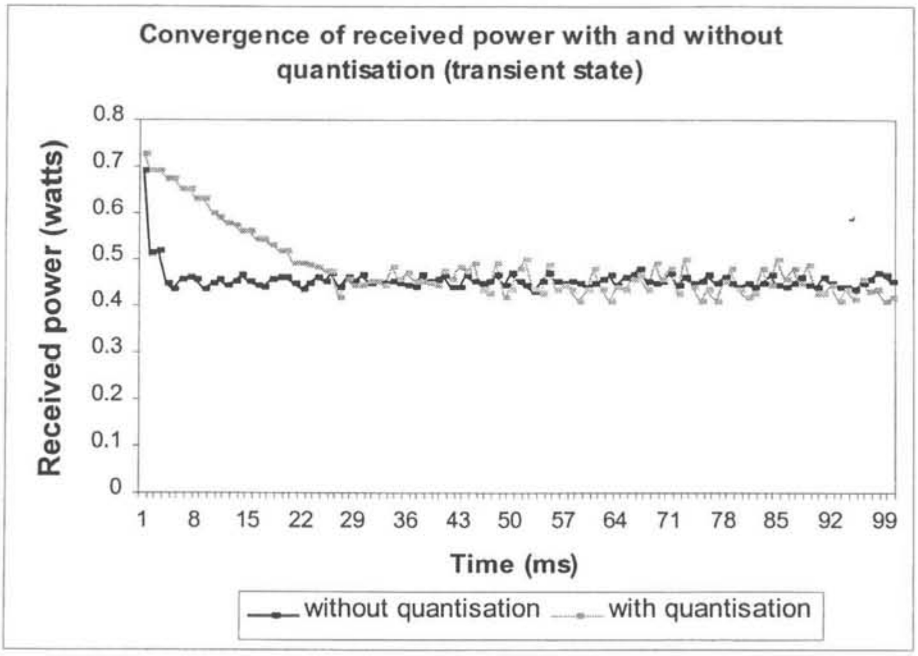

Figure 6-11 Convergence of received power with and without quantization of mobile of class I - transient state

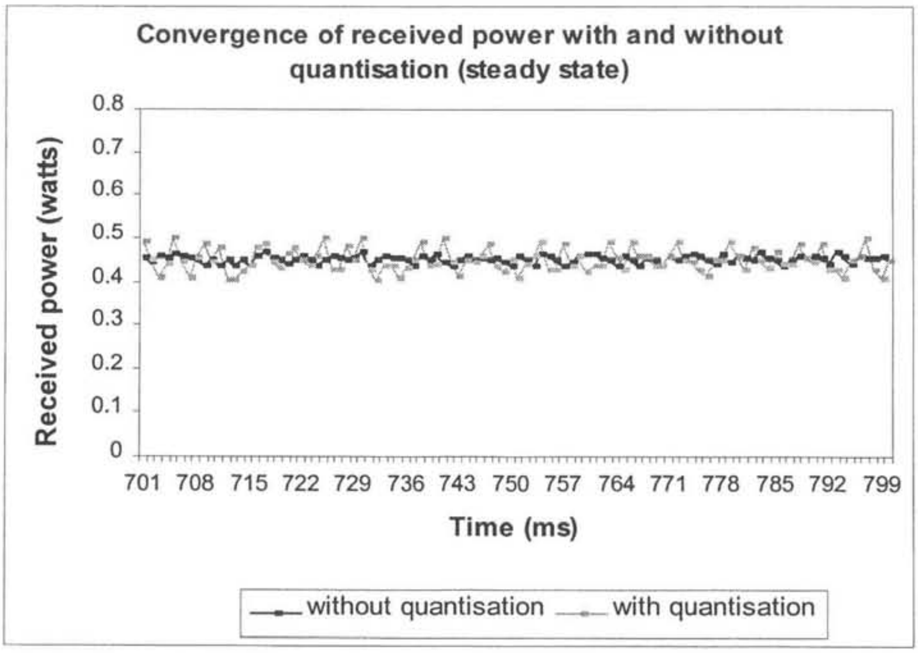

Figure 6-12 Convergence of received power with and without quantization of mobile of class I - steady state

6.9.5 Comparison of the two quantization schemes – with fixed level and with variable level

Figure 6-13 shows the received power of mobile of class I as obtained during the initial simulation run when the power levels are quantized by Δ_0 and by $\frac{\Delta_o}{2^n - 1}$. The transient state of the signal shows that the quantized scheme with $\frac{\Delta_o}{2^n - 1}$ shows a faster convergence to the required level and with a lower ripple magnitude. Figure 6-14 shows that the quantized scheme for variable step size control with a variable level $\frac{\Delta_o}{2^n - 1}$ is more stable.

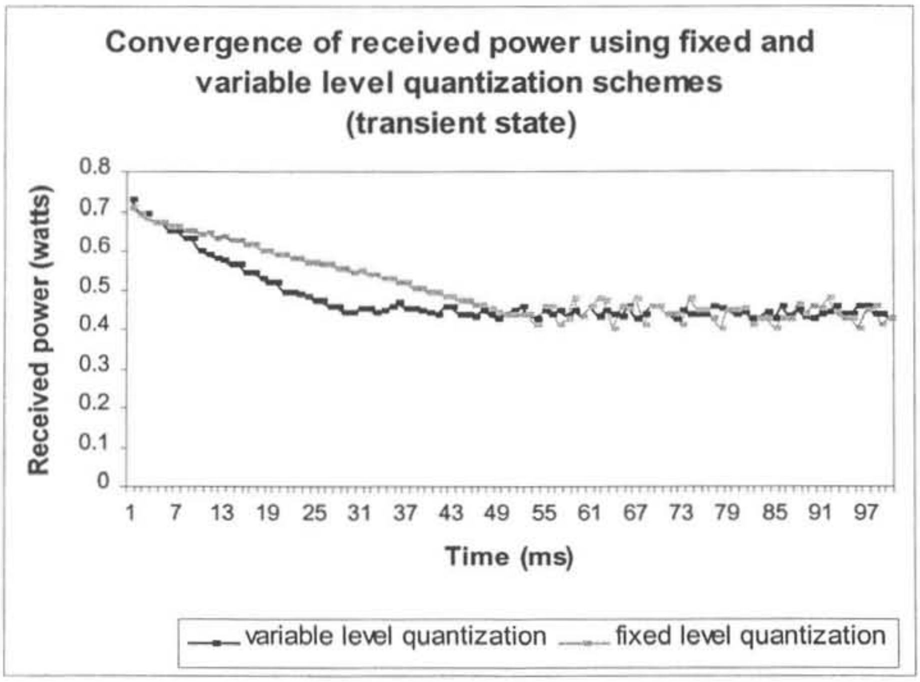

Figure 6-13 Received Power using fixed and variable level quantization schemes for mobile of class I- transient state

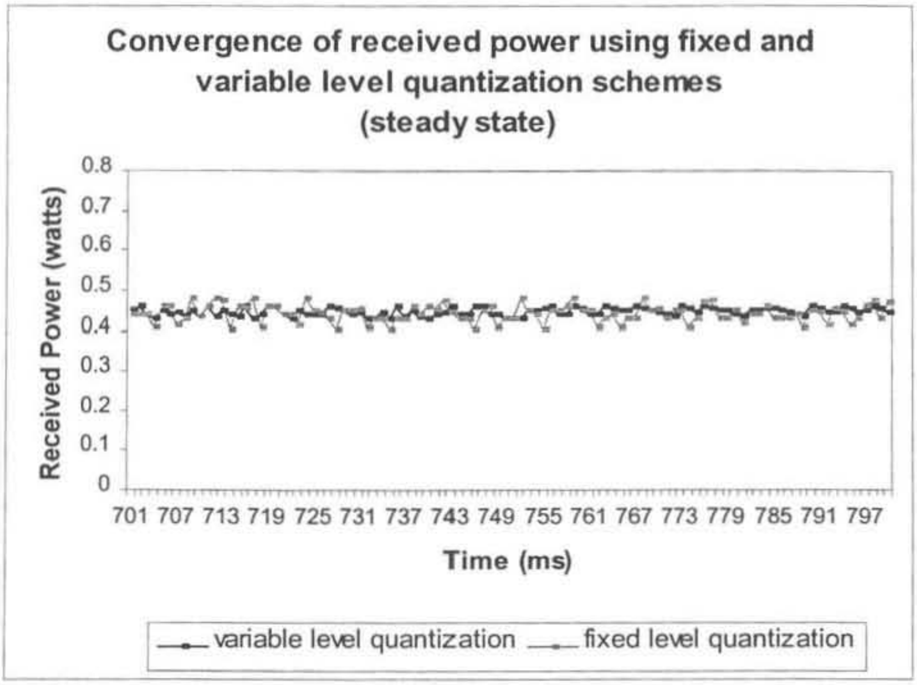

Figure 6-14 Received Power using fixed and variable level quantization schemes for mobile of class I- steady state

6.10 Summary

Pragmatic issues like Truncation of Power in CDMA communication systems and its effects are addressed in the first half of this chapter. The conventional power control schemes require a large average transmit power to compensate for fading. This exacerbates the interference caused by boundary mobiles to adjacent cells, since they typically must transmit at a very high power to compensate for fading effects. The proposed scheme, which sets a limit to the maximum power that the mobile is allowed to transmit at in case of low gain, mitigates these undesirable effects and also results in a capacity increase and provides a power gain. It shows better performance results than both the conventional power truncated scheme, which allows no transmission in case of low gain, and the scheme without truncation.

A scheme for the Power Level Quantization for a variable step size power control algorithm is proposed and its performance analyzed in the second half of the chapter. The transmission power level can take on any positive real values. However, in practice, some restrictions are inevitable. Hence, the quantization of power level is essential, though the capacity system is reduced. The received power can no longer converge to a single target but to a single target range. Although the amount of capacity reduction is difficult to quantify, it is clear that larger quantization levels result in larger reduction in capacity. The proposed quantization scheme for the variable step size power control algorithm, where the power levels are quantized by a variable level dependent on time shows better performance than when the power levels are quantized by a fixed level.

CHAPTER 7

CONTROL THEORETIC APPROACH TO POWER CONTROL

7.1 Introduction

The previous Chapters have presented a review of published power control schemes as well as our original algorithms for power control in multimedia networks. We show through simulations that these power control schemes are stable, where all the mobiles belonging to different classes of service meet with their desired QoS requirements. We however, have not proved the stability of these algorithms under all conditions. To achieve this, it is essential to employ control theoretical techniques. There has been limited work in the literature on the analysis of power control using control theoretical principles.

Practically, it is desirable to employ distributed algorithms in the network, due to extensive control signal involved with centralized schemes. These distributed algorithms can be seen as interconnected local control loops. For proper operation of a high capacity cellular radio system, besides power control, the following are the other three important aspects:

- Extracting relevant information from the available measurements.
- Design a linear power control algorithm and tune the parameters for optimized performance.
- Incorporate nonlinear components to handle constraints and priorities.

An introduction to the local analysis is given in this Chapter with focus on the components of the local loops. These can be identified as power control algorithms, time delays, static nonlinearities and filters. Some of the interesting power control algorithms can be categorized as either linear or linear with static nonlinear components. For example, some algorithms using decision feedback belong to this category. Linear systems with nonlinear components often result in an oscillatory behaviour. It is noted that early schemes neglect auto-interference in their algorithms, as its effect on stability can be treated together with the interconnections.

7.2 Local Analysis

The study uses values in logarithmic scale, which leads to a log-linear model of the power control algorithms. A general distributed control algorithm for mobile 'i' can be described as in Figure 7-1. It describes a general SIR-based power control algorithm covering the dynamics when using algorithm based on received signal power. The available measurements (possibly delayed) $\Gamma_i(n-s_m)$ are processed by filtering device F_i, which can also be seen as a model of an estimator. Based on a target value $\Gamma_o(n)$ and a processed measurement $\Gamma_i(n)$, the control algorithm R_i issues control commands $u_i(n)$. These commands may be a single bit (decision feedback) or an analog value (information feedback) or anything in between. The channel may delay the commands or corrupt them by a disturbance $x_i(n)$ modeled as additive. In the decision feedback case, it manifests itself as command bit errors and in a practical case close to information feedback, it may represent quantization noise. On the transmitter side, the possibly delay control command $x_i(n-s_p)$ is decoded by the device D_i to the updated output transmission power $P_i(n)$. In the typical information feedback case, D_i is essentially represented by a time delay. Therefore, the quantization noise x_i can without loss of generality be included in the additive disturbance $G_i(n)-I_i(n)$. The relationship between the transmitted power and SIR (neglecting auto-interference) in logarithmic scale can be given [Gunnarsson, Blom & Gustafsson1999a] as:

$$\Gamma_i(n) = P_i(n) + G_i(n) - I_i(n) \tag{7-1}$$

The physical location of devices R_i, D_i and F_i and their interpretation are irrelevant from a dynamical point of view. To emphasize the locality of the analysis, a control algorithm is referred to as a local control loop or just *local loop*. The local loops are interconnected via the interference $I_i(n)$. In local loop analysis, a simplifying assumption that $I_i(n)$ is a disturbance independent of $P_i(\tau)$, $\tau \leq n$ is made. In the case of power controlled cellular CDMA networks, the interference at one receiver is a strictly increasing function of the powers used by others. Therefore, a competition between the users can be observed and that local instabilities are not compensated for by the interconnections. Hence, local stability is a necessary, but not sufficient conditionally for global network stability.

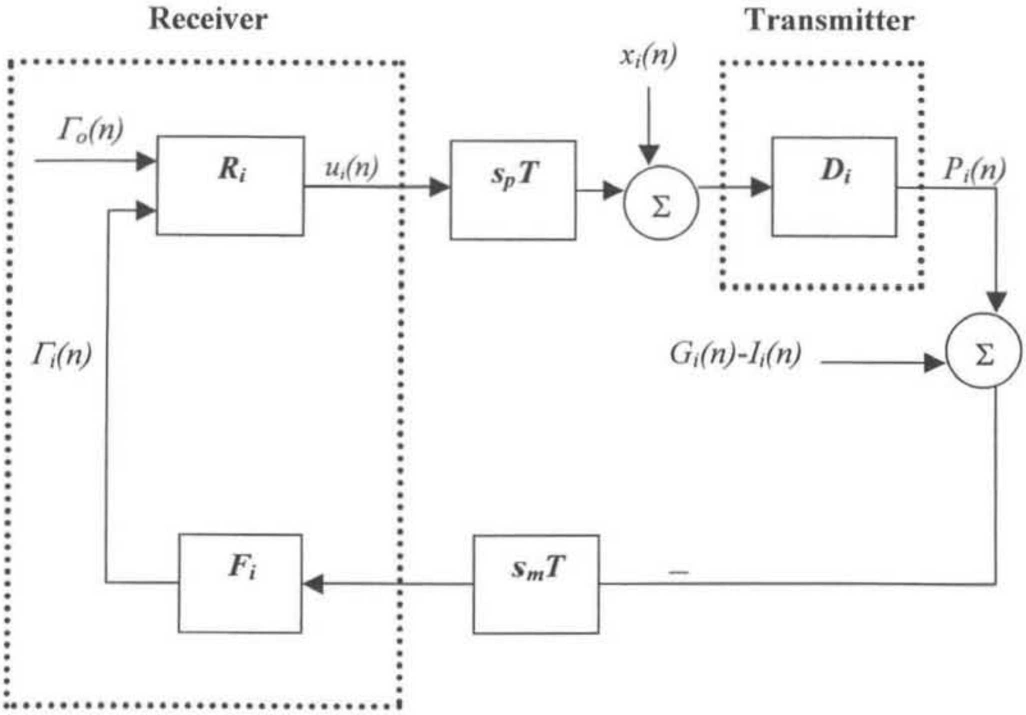

Figure 7-1 Block diagram of receiver-transmitter pair *i* when employing SIR-based closed local loop with time delays expressed in number of samples with respect to the sampling interval *T*.

Some central issues that are of concern are:

- Distributed power control is unstable when subjected to time delays
- The way time delay affects the stability of a system
- Oscillations using a fixed step power control are worse than expected when subjected to time delays

7.3 Dynamical Models

The local loops mainly comprise of four components: power control algorithms, time delays, static nonlinearities and filters. The models relate primarily to two important feedback situations [Gunnarsson, 2000]:

- **Information feedback.** The mobile feeds back the exact SIR measurements or the error:

$$e_i(n) = \Gamma_o(n) - \Gamma_i(n) \tag{7-2}$$

- **Decision feedback.** In a power control setting, this feedback is associated with the sign of the error in equation (7-2):

$$s_i(n) = sign(\Gamma_o(n) - \Gamma_i(n)) = sign(e_i(n)) \tag{7-3}$$

Thus, only one bit is needed for command signaling, which makes the scheme bandwidth efficient.

7.3.1 Power Control Algorithm

In this section, focus is laid on some important fully distributed algorithms discussed in section 3.6.2.2 and as to how these algorithms relate to the following algorithm, based on information feedback:

$$P_i(n+1) = P_i(n)\left(\frac{\Gamma_o(n)}{\Gamma_i(n)}\right)^{\beta_i} \tag{7-4}$$

If the update frequency of $\Gamma_i(n)$ is much slower than the time constants of the control algorithm, it is seen that it is considered as constant in the analysis. It is instructive to express this control law in logarithmic scale [Gunnarsson, 2000] as:

$$P_i(n+1) = P_i(n) + \beta_i(\Gamma_o(n) - \Gamma_i(n)) \tag{7-5}$$

This controller is identified as an *integrating (I) controller*.

The algorithm proposed by Lin [1995] can be rewritten as:

$$P_i(n+1) = P_i(n)\left(\frac{\beta_i^{1/\xi_i}}{\Gamma_i(n)}\right)^{\xi_i} \tag{7-6}$$

where β_i and ξ_i are design parameters.

Similarly, the Distributed Power Control algorithm [Foschini & Miljanic, 1993] in equation (3-8) is obtained as the special case with $\beta_i = 1$ and constant Γ_o. The equation adopted from Yates [1995] compile to:

$$P_i(n+1) = P_i(n) + (1-\beta_i)(\Gamma_o - \Gamma_i(n)) \tag{7-7}$$

This is similar to equation (7-5) if the controller parameter β_i is redefined and a constant target value is utilized. The algorithm proposed by Almgren, Andersson and Wallstedt [1994] is also related as:

$$P_i(n+1) = \alpha_i - \beta_i(\Gamma_i(n) - P_i(n)) = P_i(n) + \beta_i\left(\frac{\alpha_i}{\beta_i} - \frac{1-\beta_i}{\beta_i}P_i(n) - \Gamma_i(n)\right) \tag{7-8}$$

This can be seen as the algorithm in equation (7-5) with a power level dependent target SIR. The local dynamics are more emphasized in the following form:

$$P_i(n+1) = \beta_i P_i(n) + \beta_i(\Gamma_o - \Gamma_i(n)) \tag{7-9}$$

where $\Gamma_i(n) = \alpha_i / \beta_i$ is a design parameter, provided by an outer control loop. Using decision feedback, the control error $e_i(n) = \Gamma_o(n) - \Gamma_i(n)$ is not available. In algorithms based on the desired signal power, the interference is considered as an independent disturbance to the local loop. Therefore, the closed-loop dynamics of the local loops are identical for SIR based and signal power based algorithms.

The I-controller and power control with integral action are only plausible when the power control problem is *feasible* i.e., when it is possible to find transmission powers to meet the desired target values. Therefore, these algorithms need this underlying assumption. The assumptions do not affect the local loop analysis, but relate to global stability.

7.3.2 Time Delays

Both measuring and signaling in communication systems take time, which result in delayed signals. As pointed out in section 3.5, there are three main reasons for time delays. Firstly, the power control algorithm R_i is assumed to result in a time delay of one sample, since measurements at time '*n*' (example $\Gamma_i(n)$) are used to update the power level at time '*n+1*' (example $P_i(n+1)$). Secondly, it takes some time before a computed power level actually is used and thereby observed by others. Additional delays are caused by the fact that power update commands are only allowed to be transmitted at certain time instants. Together they result in a total delay of s_p samples. Finally, the measuring procedure takes time, and again these measurements are only reported to the power control algorithm at certain time instants, resulting in a delay of s_m samples. In total there is an additional delay of $s = s_p + s_m$ samples in the local loops. A typical delay situation example is illustrated in Appendix A-2.

The time variant interval over which measurements are collected is normally a fraction of the power control update interval. Therefore, it is natural to define time instants '*n*' equal to the update instants of the transmission power, which are fixed and can be associated with the power control update interval N_s.

Time delays are represented using the time-shift operator 'q' defined by:

$$q^{-s}P(n) = P(n-s), \quad q^{s}P(n) = P(n+s) \qquad \textbf{(7-10)}$$

To stress the direction of the time shift, the terms *forward-shift operator* and *backward-shift operator* (or *delay operator*) are used for q and q^{-1} respectively [Åström & Wittenmark, 1997].

7.3.3 Nonlinearities

System nonlinearities are often classified as either *inherent* or *intentional* nonlinearities. The first category consists of components that affect in the design at the moment, such as output power constraints. On the other hand intentional nonlinearities are those, which are deliberately introduced in the system.

Due to physical limitations in the hardware, the output power levels are bounded and in addition, the power levels are quantized as discussed in Chapter 6. Usually, these nonlinearities are referred to as constraints. There are also nonlinearities introduced by the software. In some standards, there are channels requiring the use of maximal powers as when using different channels during a call. These nonlinearities are inherent and affect the output powers. It is also possible to incorporate nonlinearity in the power control algorithm, as the *sign function* or *relay* in the decision feedback algorithms.

7.3.4 Filters

The measurements or estimates may be corrupted by noise and therefore a filter *F(q)* is applied in order to even out rapid fluctuations due to noise. A different interpretation is that *F(q)* represents a model of an implemented estimation procedure, whose dynamical effect on the local loop is of interest. The filter *F(q)* is completely arbitrary, but some of the common choices are [Gustafsson, 2000]:

- **Local Average**. If the instantaneously measured SIR at time '*n*' is $\Gamma'_o(n)$ then the filtered SIR is $\Gamma_o(n)$. The output of the filter is the mean value of the last *L* input values:

$$\Gamma_o(n) = \frac{\Gamma'_o(n) + \dots\dots\dots\dots + \Gamma'_o(n-L+1)}{L} \qquad \textbf{(7-11)}$$

Using the time-shift operator *q*, the filter is described by:

$$F_{LA}(q) = \frac{1 + \dots\dots\dots\dots + q^{-L+1}}{L} \qquad \textbf{(7-12)}$$

The parameter *L* is commonly referred to as the *sliding window length.*

- **Exponential Forgetting**. In the previous approach, the values are weighted together using an equal weight. A batch containing the last *L* values is also needed. Another approach is to weigh the input values $\Gamma'_o(n)$ differently, using larger weights on the more recent values. This can be achieved by the following recursion, where the inputs are given by $\Gamma'_o(n)$ and the filter output by $\Gamma_o(n)$.

$$\Gamma_o(n) = \lambda\Gamma_o(n-1) + (1-\lambda)\Gamma'_o(n), \quad 0 \le \lambda < 1 \qquad \textbf{(7-13)}$$

The filter $F_{EF}(q)$ can be written as:

$$F_{EF}(q) = \frac{(1-\lambda)q}{q-\lambda} \tag{7-14}$$

The number of values that essentially contribute to the filter output depends on the *forgetting factor* λ.

In practice, the signal and the interfering powers might be estimated separately. Consequently, it is beneficial to employ separate filters as shown in Figure 7-2. The filter of the interfering power is typically much slower (as λ is much closer to unity) than the signal power filter. Since, the focus of the study is on stability of the local loops, only filters applied on SIR are considered. This is the same as focusing on the signal power filter $F_g(q)$.

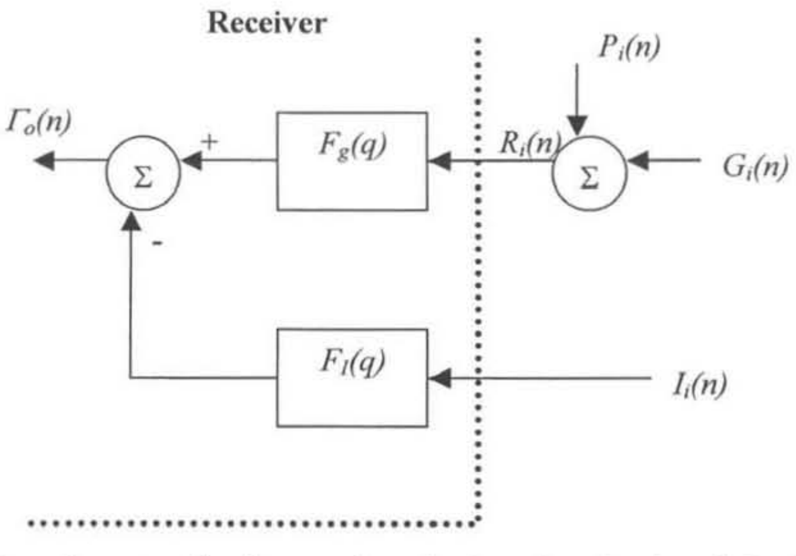

Figure 7-2 Separate filtering employed when the signal and the interfering powers are available.

7.4 Log-Linear Algorithms

In several cases, the nonlinearities in the local loops can be neglected, and thus the remaining system to be analyzed is linear. An example of which is illustrated in Appendix A-3. Local loop stability can therefore be addressed using linear systems theory methods. Root locus analysis is applied to power control problems.

The distributed power control algorithm can be generalised to:

$$P_i(q) = R(q)[\Gamma_o(q) - \Gamma_i(q)] \tag{7-15}$$

where *R(q)* in the case of the I-controller in equation (7-5) is given by:

$$R(q) = \frac{\beta_i}{q-1} \tag{7-16}$$

The output from the controller $P_i(n)$ cannot depend on the input instantaneously. Therefore, *R(q)* has to contain at least one delay. The terms *instability* and *stability* of a local loop have to be well defined. Rather simplified, instability comes about when relying too much on outdated information. This results in over-compensation, which is aggravated over time. Eventually, the transmission power oscillates between its upper and lower output constraints. A system may also be marginally stable, where a stable oscillation in the output power is observed. In a stable local loop, the effects of stepwise disturbances and target SIR changes decay to zero over time. The stability is discussed in terms of the property *uniform asymptotic stability*. It implies that transients decay to zero asymptotically.

7.4.1 Stability of Linear Systems

A discrete-time linear system with one input *u(n)* and one output *y(n)* is considered. Using the time-shift operator *q*, a system can be described using the transfer function *G(q)* as [Gunnarsson, Gustafsson & Blom, 1999b] :

$$Y(q) = G(q)U(q) = \frac{B(q)}{A(q)}U(q) = \frac{b_1 q^{-1} + b_2 q^{-2} + ... + b_{n_b} q^{-s_b}}{1 + a_1 q^{-1} + ... + a_{n_a} q^{-s_a}}U(q) \quad \textbf{(7-17)}$$

The poles of the transfer function are defined as the roots of the *A(q)* polynomial.

When using feedback, the closed-loop system is depicted as in Figure 7-3, where *G(q)* denotes the system to be controlled, *R(q)* denotes the controller and *S(q)* denotes the sensor dynamics or a filter.

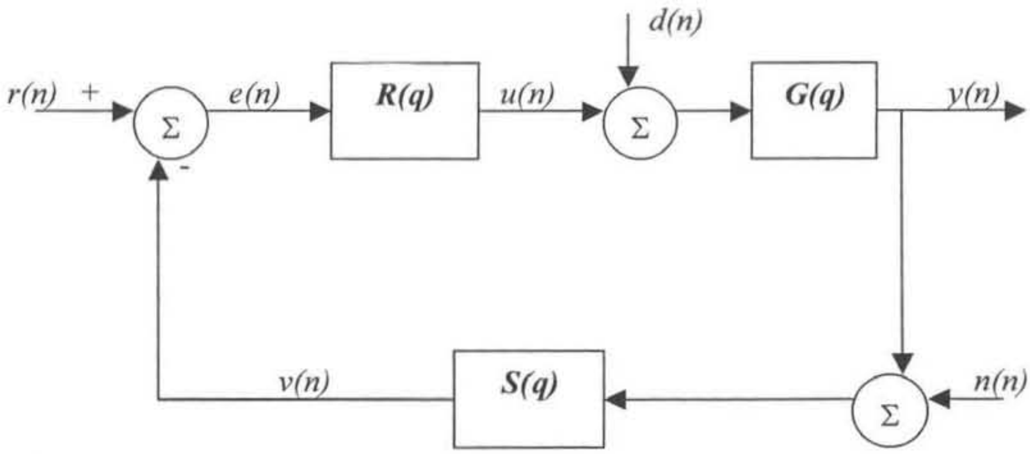

Figure 7-3. The basic feedback loop

The *closed-loop poles* are defined as the roots of the characteristic polynomial. A different, but analogous representation of the linear system in Figure 7-3 is the following state space representation [Gunnarsson, Gustafsson & Blom, 1999c]:

$$x(n+1) = \mathbf{A}x(n) + \mathbf{B}\,(r(n), d(n), n(n))^T \quad \textbf{(7-18a)}$$

$$y(n) = \mathbf{C}x(n) + \mathbf{D}\,(r(n), d(n), n(n))^T \quad \textbf{(7-18b)}$$

where ***A***, ***B***, ***C*** and ***D*** are matrices and *x(n)* is the state vector.

When nonlinearities in the local loop cannot be neglected, *describing functions* based on assumptions of *oscillations* or *limit cycles* in the loop is utilized. The study showed that much of the available works analysis primarily aim at studying the effects of *relays* in discrete-time linear control loop [Blom & Gunnarsson, 1998], [Gunnarsson, Gustafsson & Blom, 1999b]. In an inner loop control systems, the power is updated according to:

$$P_i(n+1) = P_i(n) + \Delta sign(\Gamma_o + \Gamma_i(n)) \qquad \textbf{(7-19)}$$

where Δ is the step size in dB. The sign function can schematically be represented as a relay. The main incentive for using the relay is the bandwidth efficient binary command signaling that can be used when the update rate is high.

7.5 Log-linear algorithms with a static nonlinearity

The static nonlinearities, such as a relay or a sign function are seen to result in an oscillatory behaviour of the system. These oscillations may comprise of several modes. Switching between the modes may be stimulated by external disturbances. It is seen that for analysis purposes, describing functions are introduced and applied to local loops consisting of a static nonlinearity and a linear part. Thereby, prevalent oscillations can be predicted. Using the discrete-time describing functions, the oscillations observed in a power control algorithm can be predicted. The dynamical behaviour of the fixed step power control algorithm can be given as:

$$P_i(n+1) = P_i(n) + \beta_i sign(\Gamma_o(n) - \Gamma_i(n)) \qquad \textbf{(7-20)}$$

7.6 Effect of Auto-Interference

The effect of the auto-interference on local loop stability was seen to be a neglected feature in the topics covered in the study so far. Nevertheless, a brief analysis is done by Gunnarsson [2000]. In essence, the effect of the auto-interference is brought into the linear systems theory framework by linearizing the interference. The effect of the auto-interference is seen to be a smaller step size in reality. According to describing function, the amplitude of the oscillations is smaller. Hence, the auto-interference does not violate stability of linear algorithms nor aggravate oscillations of the power control algorithm.

7.7 Summary

A study done on the control theoretical approach to power control shows that the global system can be seen as a number of local control loops, interconnected via the interfering powers between the users. Local loop stability is seen to be necessary for global stability. It is seen that local loop analysis provides valuable insight in the dynamical behaviour of power control algorithms. Primarily two classes of algorithms are considered in the work presented. The first class includes most of the interesting classes of algorithms utilizing information feedback. They are seen as linear controllers in logarithmic scale, and thus properties of linear systems are relevant. Using root locus analysis from control theory, stability is addressed with respect to the controller parameters.

Controllers such as the fixed step power control algorithm that utilize decision feedback, behave slightly different. The decision component can be seen as a sign function or a relay and has both stabilizing and unstabilising effects. This static nonlinearity results in an oscillatory behaviour, which neither vanishes nor aggravates over time. Several oscillation modes are possible, and mode switching is stimulated by external disturbances. Study on dynamical effects of imperfect receivers shows that auto-interference does not violate stability of linear algorithms nor aggravate oscillations of the power control algorithms.

CHAPTER 8

CONCLUSIONS

The main focus of this thesis has been on *power control* in *multimedia CDMA* cellular networks. This work has been prompted by the success of CDMA as a viable multiple access technique. Some advantages of CDMA over other multiple access techniques include higher spectral reuse efficiency, greater immunity to multipath fading, gradual overload capability, simple exploitation of sectorisation and more robust handoff procedures [Lee, 1991], [Kohno, Meidan & Milsein, 1995]. There has been a lot of interest in the research community on the design and performance analysis of receivers, coding and modulation techniques, and power control algorithms. The driving incentive is to enable and facilitate communication services irrespective of time and location. As the number of users and the demand for multimedia services increase, so does the need for efficient use of the available radio resources. Appropriate radio resource management is therefore of utmost importance.

Hence, the assignment of base stations, radio channel (or waveform or code) and transmission powers of each connection have to be regularly reconsidered.

In Chapter 1, we gave a simple introduction to the concepts, challenges and future requirements of a global information infrastructure incorporating the next generation of wireless multimedia networks. We focused in this thesis on the study and derivation of new QoS based techniques for power control in multimedia CDMA system. We addressed the main aim of the thesis – the challenge of integrating heterogeneous transmitting sources with a broad range of QoS characteristics in the cellular CDMA networks. Provided the right power control can be devised, CDMA offers the potential of extracting gain from the statistical multiplexing of such sources. The focus and goals, and motivation of this thesis research were also presented.

Chapter 2 reviewed a journey of the CDMA evolution towards the wideband CDMA network. It gave an introduction to CDMA, describing in detail its concepts and basic elements such as multiple access capability, soft handover, interfrequency handover, and multiuser detection. Features of the IS-95 CDMA air interface, with a focus on the new downlink and uplink channel structures were discussed. An introduction to the air interface technologies for Third Generation was given. Parameters of WCDMA in Europe and Japan, cdma2000 in the USA, and wideband CDMA in Korea were compared.

Chapter 3 gave an in depth literature survey on traditional power control schemes, with focus on those relevant for single-service CDMA network. A general model for power control and the main aim of power control was presented at the outset, which was followed by an examination of the different types that a power control scheme can be categorised as. A framework model for power control identifying the dominant factors and channel quality criteria such as: signaling and modulation schemes, link orientation, environment morphology and topology, speed of mobile user, cell hierarchy and connection type was discussed. An introduction of the various aspects of power control which include the capacity and load of the system, centralized or distributed power controller, global stability and performance, quality measures, feedback measure, hardware constraints and was also given. Finally, a detailed discussion on the previous proposed power control schemes was covered based on their type, aim and derivation procedures.

Chapter 4 reviewed the various power control schemes with focus on those relevant for multi-service wireless applications. Factors influencing QoS in multimedia network were discussed. A detailed description on power control structure for multimedia traffic characterisation was given which aims at classifying the various upcoming services according to their traffic characteristics. A detailed survey on the earlier proposed power control algorithms in multimedia CDMA network was presented which covered most of the important and central contributions made so far.

In Chapter 5, we have proposed, derived and investigated the performance of a distributed variable step size power control algorithm in a cellular CDMA network, which supports heterogeneous transmitting sources having diverse characteristics and Quality of Service requirements. The power control algorithm is a discrete-time feedback adjustment power control scheme. It updates the transmitted power of the mobiles in each of the service classes by a variable step size and the only information needed to adjust the transmission power of the mobile terminal is the received SIR at the corresponding base station. The speed, at which the power control is performed, depends on the algorithm proposed which designs the step size. This step size is not only required to adjust the transmitted power so as to meet with the QoS, but to follow channel variations also. The variable step size helps in the fast convergence of the SIR to the assigned value and this can be attributed to the step size constant k_o. Results obtained helped us to conclude that higher the value of k_o, faster is the convergence of SIR to the desired value. The received power and the SIR for each of the service classes are adapted locally based on the measurements of the mean and variance of the interference caused by the other active mobile users operating in the system. These factors account for giving the algorithm a more practical approach.

The results show the fast convergence of the adapted power levels to their optimum levels fulfilling the QoS requirements. The step size efficiently adjusts and regulates the transmitted powers. Variable step size power control in comparison with fixed step size power control, showed better performance by converging at a much faster rate and remaining constant at that level. Both the received SIR and the received powers at the base station remain constant at the required levels thereby helping us to conclude that the proposed power control scheme is stable.

Chapter 6 provided the incorporation of two pragmatic issues, namely, truncation of transmit power and quantization of power levels, into our proposed variable step size power control algorithm. The conventional power control schemes require a large average transmit power to compensate for fading. This deteriorates the system performance, as it worsens the interference caused by the boundary mobiles, since they transmit at very high powers to compensate for fading effects. Our proposed scheme, which sets a limit to the maximum power that the mobile is allowed to transmit at, even in case of low gains, mitigates these undesirable effects. It shows better performance results than both the conventional power truncated scheme, which allows no transmission in case of low gain, and the scheme without truncation. Quantization of power levels is essential since in practice, the transmission power levels cannot take on any positive real values. The received power can no longer converge to a single target but to a single target range. Although the amount of capacity reduction is difficult to quantify, it is clear that larger quantization levels result in larger reduction in capacity. We derived two quantization power level schemes for the variable step size power control algorithm. The proposed quantization scheme, where a variable level dependent on time quantizes the power levels, showed better performance than when the power levels are quantized by a fixed level.

Chapter 7 focused on a study done on the control theoretical approach to power control. The power control operation of a system can be studied at two levels by separating the time scales, namely, the global level and the local level. On a global level, the focus is on capacity, load, stability, convergence and whether it is possible to meet the service requirements from the users. Local aspects include dynamical effects of time delays and nonlinear components, and the ability to mitigate time-varying disturbances. An important categorization of the inner loops is whether it utilizes information feedback, where real-valued measurements are assumed available, or decision feedback, which relies on decisions; typically the sign of the control error. The study showed that most central information feedback algorithms can be associated with linear local control loops, and thus methods from linear systems theory apply. Decision feedback controllers behave differently. The decision component can be seen as a sign function with inherent stabilising and destabilising properties. The study showed that in a closed local loop, this results in a persistent oscillative behaviour. Several oscillation modes are possible and the mode switching is stimulated by external disturbances.

This thesis has presented a comprehensive and accurate methodology for the study of power control in a multimedia multicellular CDMA radio network. Finally, to conclude this thesis, we present some possible extensions and/or further topics of study to this research.

- In Chapter 5 we obtained the step size parameter δ_{ij}^{*} through experimentation. As a possible extension, we propose the derivation of an expression to predict δ_{ij}^{*} based on a given set of network parameters.

- Similarly, we suggest the derivation of an expression to predict the optimum value for QoS parameters α_j and v_j, based on the given network parameters.

- Control theoretical analysis of the derived algorithms to determine stability margins.

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APPENDIX

A.1 Evolution of Mobile Communications

Generations	Type	Time	Description
First	Analog	1980s	Voice centric, multiple standards (NMT, TACS etc.)
Second	Digital	1990s	Voice centric, multiple standards (GSM, CDMA, TDMA)
2.5	Higher Rate Data	Late 1990s	Introduction of new higher speed data services to bridge the gap between the second and Third Generation, including services such as General Packet Radio Services (GPRS) and Enhanced Data Rates for Global Evolution (EDGE)
Third	Digital Multimedia	2010s	Voice and data centric, single standard with multiple modes

Table A-1 Source Mobile Lifestreams

A.2 Typical Delay Situation in WCDMA

Since the command signaling is standardized, the delays are known exactly in number of samples (or slots). Typical situations in WCDMA are depicted in Figure A-1.

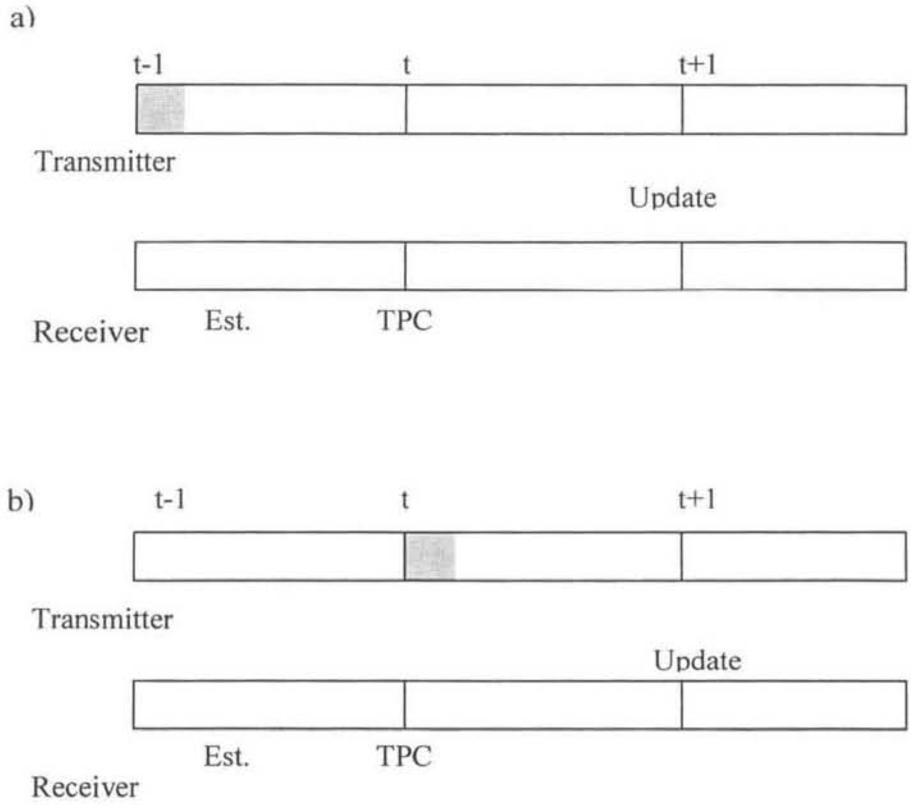

Figure A-1 Typical time delay situation in WCDMA. Command signaling and power updates take place as indicated.

a) $s_p = 1, s_m = 0$

b) By shifting the slot configuration, s_p can be brought down to zero when the mobile station is close to the base station.

In a) the receiver estimates the SIR $\Gamma_i(n)$ (possibly only the desired signal power, which is combined with a separate interference measurement to compile SIR) over some pilot bits and data symbols, on a slot sent using the power $P_i(n+1)$. The power control command is included in a slot in the opposite direction at time instant n. The transmitter finally updates the power $P_i(n+1)$.

By shifting the slot synchronisation as in b), the transmitter power can be controlled without excessive loop delay. The drawback is that fewer bits for the SIR estimation are used, resulting in a larger variance of the estimation error. This is only possible for mobile stations relatively close to the base station, and $s_p = 1$, $s_m = 0$ is considered as a typical WCDMA situation.

A.3 Local Loop of Distributed Power Control and Delayed Output Powers

When a distributed power control algorithm is considered [Gunnarsson, 2000],

$$P_i(n+1) = P_i(n) + \Gamma_o - \Gamma_i(n)$$

Using the time-shift operator, this corresponds to:

$$P_i(n) = \frac{1}{q-1}\left(\Gamma_o - \Gamma_i(n)\right)$$

The computed output powers are delayed by one sample before they are actually used by the corresponding transmitter. Thus, the SIR can be given as:

$$\Gamma_i(n) = P_i(n-1) + G_i(n) - I_i(n)$$

Hence, the algorithm in closed-loop can be depicted as in Figure A-2

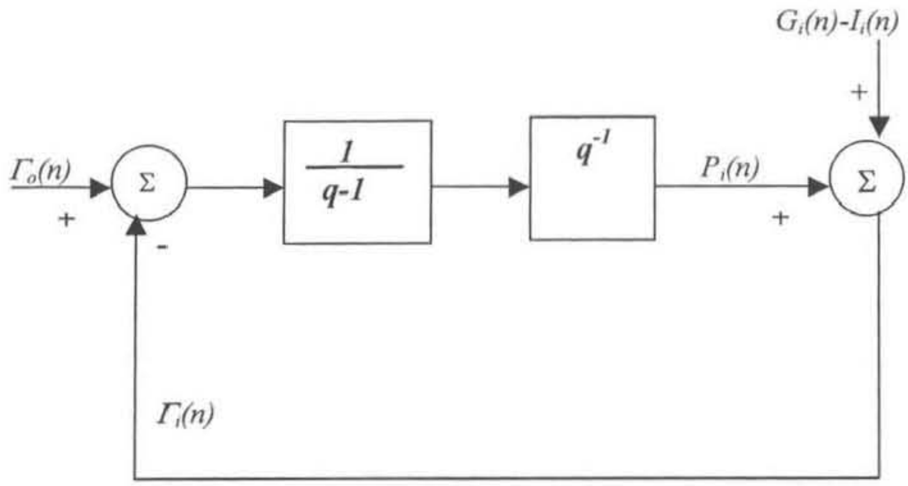

Figure A-2 The local loop using distributed power control, when the computed output power is delayed by one sample.