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Estimation of Radio Resource in a 3G Multimedia System through Simulation

By

Chiew-Leong Saw, B. Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical and Computer Engineering
Faculty of Engineering
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submitted by
Chiew-Leong Saw, B. Sc.
in partial fulfillment of the requirements for
the degree of Master of Engineering

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Abstract

This thesis describes the procedures to estimate the Erlangs Capacity of two inherently different traffic services: Circuit Switched Voice and Circuit Switched Data traffic services that a multi-rate Code Division Multiple Access (CDMA) cellular system can support. The system capacity on the Forward Link will be estimated through simulations.

Our simulation is also to show how imperfect orthogonality of the Forward Link channels affects the overall capacity estimated and system performance. In addition, this thesis will also provide an analysis on some critical scenarios where a group of users with specific properties are more vulnerable to changes in traffic distributions, i.e., how the system discriminates one service over another under some circumstances. The interaction between two traffic services and the effects of these interactions have on the system capacity and performance will also be investigated.

A simulator is built to simulate this simplified and integrated Voice and Data cdma2000 cellular system. It could be used as a basis for future research in areas such as Admission Control, Radio Resource Management, etc.

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List of Acronyms

3G	Third Generation
BER	Bit Error Rate
BS	Base Station
CDMA	Code Division Multiple Access
CLPC	Closed Loop Power Control
DCCH	Dedicated Control Channel
DS	Direct Sequence
FCH	Fundamental Channel
FDMA	Frequency Division Multiple Access
FL	Forward Link (Down Link)
GoS	Grade of Service
HHO	Hard Handoff
HO	Handoff
MS	Mobile Station
PCH	Paging Channel
PICH	Pilot Channel
PN	Pseudo Noise
QoS	Quality of Service
RL	Reverse Link (Up Link)
RRM	Radio Resource Management
SCH	Supplemental Channel
SHO	Soft Handoff
SINR	Signal-to-Interference-plus-Noise Ratio
SYNCH	Synchronization Channel
TDMA	Time Division Multiple Access

1 INTRODUCTION

The explosive growth of the Internet and the continued dramatic increase in demand for all types of wireless services are fueling the demand for large increases in capacity, data rates and supported services. The high data rates promised by Third Generation (3G) wireless technology is expected to play an important role in enabling wireless service operators to offer a broader range of services. As shown below, four generic types of services have been identified [1]:

1. Basic and enhanced voice services, including applications such as audio conferencing and voice mail.
2. Low data rate services supporting messaging, email and facsimile.
3. Medium data rate services for file transfer and Internet access at rates in the order of 64 – 144 kbps.
4. High data rate services to support high speed packet and circuit switched network access and to support high quality video conferencing and networked computing applications at rates in the order of 64 kbps – 2Mbps.

In addition to the above generic service types, the 3G systems will be required to deliver multimedia services, which provide concurrent video, audio and data services to support advanced interactive applications utilizing advanced multiple access techniques such as Code Division Multiple Access (CDMA). These services are also capable of supporting different quality of service (QoS) requirement for different applications.

Cdma2000 is a North American proposal for 3G cellular systems submitted to the International Telecommunication Union (ITU). As a 3G system, the cdma2000 systems

include a greatly enhanced air interface supporting CDMA over wider bandwidths of 5MHz and beyond for improved capacity and a wide range of data rates (9.6 kbps – 2 Mbps) while maintaining backward compatibility with existing IS-95 CDMA cellular systems[1]. The issues in system architectural designs, Radio Resource Management (RRM) and methods for efficient integration of these multimedia wireless services in cdma2000 are important research areas.

Since CDMA systems are interference-limited, the classical Erlang B formula [2] that is used to calculate the capacity of the radio resources in bandwidth-limited systems cannot be applied here. Hence a new method is needed to evaluate the capacity of an integrated Data and Voice cellular system like cdma2000.

Asymmetric traffic between the Forward Link (FL) and the Reverse Link (RL) in the Internet web browse and data download applications is a realistic scenario. Usually, traffic load on the FL is much heavier than that on the RL because of the difference between the large size WWW download and ftp pages, which are carried over on the FL, and the user-initiated short request messages, which are carried over on the RL. Thus, a larger capacity on the FL is needed and this study is limited to estimate the capacity on the FL only.

In the study, a dynamic simulation method to accurately estimate the capacity of 3G cellular systems based on cdma2000 scheme is presented. In addition, the same simulator will be used to demonstrate how the system capacity and performance are affected by the FL orthogonality factor.

1.1 Objectives

The primary objectives of this thesis are as follows:

1. To estimate the FL Erlang capacity of the multi-rate cdma2000-based cellular system through simulation;
2. To evaluate how imperfect orthogonality of the FL channels due to multipath affects the system capacity and performance; and
3. To evaluate how the system discriminates one type of traffic service over another.

1.2 Organization

The thesis is organized as follows: Chapter 2 explains the fundamental of spread spectrum technology followed by the definition of CDMA capacity and the motivations and needs to measure this capacity. Reviews of prior work and brief descriptions on how to achieve the objectives outlined above are explained. Chapter 3 describes the details of the system level simulation and modeling. Chapter 4 explains some important call handling protocols that are used in the simulation. Chapter 5 describes the simulation strategy used to estimate the capacity through steady state simulation. Chapter 6 describes how simulation cases are selected and how initial conditions for simulations are chosen. Chapter 7 discusses and compares test cases and the simulation results. Concluding remarks are presented in Chapter 8. Finally, some suggestions for future development are presented in Chapter 9.

2 CDMA Cellular Systems

In this chapter, some useful background information, concepts and terminology about CDMA cellular systems are reviewed. This review provides the technical and theoretical information necessary to fully understand the descriptions and explanations of this study given in subsequent chapters.

2.1 Spread Spectrum Principles

Spread spectrum multiple access (SSMA) communication, known commercially as Code Division Multiple Access (CDMA), is a driving technology behind the rapidly advancing wireless communications industry. Its greater bandwidth efficiency and multiple access capabilities make it the leading technology for relieving spectrum congestion caused by the explosion in popularity of cellular mobile and fixed wireless data terminals.

Spread spectrum multiple access does not attempt to allocate disjoint frequency or time resources to each user. Instead, it allocates the entire bandwidth resources to all simultaneous users (i.e., universal frequency reuse). It spreads the bandwidth of the transmitted signal over a spectrum or band of frequencies many times greater than the information bandwidth or data rate of any user making the signal appear wideband and "noise-like". The ratio of bandwidth in hertz to the data rate in bits per second is the bandwidth spreading factor or processing gain. One of the most important spread spectrum applications is enabling multiple access communication by a large population of relatively uncoordinated users of a common spectral allocation in the same and

neighboring geographical areas, with the number of simultaneous users proportional to the processing gain.

Among all the spread spectrum techniques, the Direct Spreading (DS) implementation is the most popular. In DS, a narrowband signal is spread by a wide bandwidth Pseudo-Noise (PN) code. A different PN code is assigned to each signal, and at the receiving end the signals are extracted out of the background noise by a receiver that correlates the received signals with a copy of the original PN code. Since the PN codes are generated by Walsh functions that are mathematically shown to form an orthogonal set, all other signals with codes that do not match with the receiver are filtered out.

In a cdma2000 cellular system, multi-rate Voice and Data services are to be supported concurrently. Reallocation of codes and so on is normally not needed as the bit rate demand changes, which means the physical channel allocation remains unchanged even if the bit rate changes. All that is needed is to adjust the assigned power level to reflect changes in bit rates or Quality of Services (QoS) requirements. This flexibility is supported in the CDMA systems with the use of orthogonal variable spreading factor (OVSF) codes. These codes are referred to as channelization codes [3]. The OVSF codes have the characteristics of maintaining FL channels orthogonal between users even if they operate at two different bit rates. One physical resource can thus carry multiple services with variable bit rates. As the bit rate demand changes, the power allocated to this physical resource is adjusted such that the QoS is maintained at all times during the call duration. Therefore, power as a common shared radio resource for all users becomes one of the most important characteristics of DS-CDMA cellular systems.

On the FL, the total transmitted power of an RF carrier is the true radio resource that is being shared among all mobile users or mobile stations (MSs) in the cell. On the RL, there is a maximum tolerable interference level at the base station (BS) receiver. This aggregate maximum interference power is the main radio resource. In other words, each MS is allowed to cause a certain level of interference. The maximum number of MSs is determined by the maximum tolerable aggregate interference. For these reasons, power makes DS-CDMA cellular systems very flexible in handling mixed traffic services and traffic services with variable bit rate demands.

Since the entire bandwidth is allocated to all simultaneous MSs in the system, all MSs in a CDMA cellular system must contend not only with co-channel interference from the neighboring cells, but also with co-channel interference within the same cell. Ideally, there is no same-cell interference on the FL because the different CDMA FL channels are orthogonal. However, the wireless propagation channel introduces same-cell interference because of multi-path receptions at the MS's location. In addition, in practice, as the square Walsh functions are passed through real-world radio frequency (RF) and intermediate frequency (IF) filters, they may not stay orthogonal and the self-interference of the system may not be zero. According to the severity of the channel and filter conditions, a degree of same-cell interference is experienced. This is known as the orthogonality factor on the FL. FL orthogonality factor of zero denotes that a MS suffers no same-cell interference [4]. On the RL, the BSs must contend with the superposition of signals from all MSs both in the same cell and neighboring cells.

Since all resources are allocated to all simultaneous users, power control is required to control the power allocated to each MS on the FL or power transmitted by each MS on the RL to the minimum required to maintain a given signal-to-interference-plus-noise ratio (SINR) for the required level of performance. Power control plays a critical role in managing the co-channel interference and overcoming the near-far problem to achieve maximal system capacity.

In a power controlled DS-CDMA system, the number of MSs that each cell can support is limited by the total co-channel interference received at each MS and will vary with time. When a system is congested, admitting a new MS can only degrade the communication link quality for ongoing active calls and may eventually lead to call droppings. Thus, an admission control is needed to control the number of MSs the system should grant access to. In a system that supports mixed traffic services, an effective admission control algorithm should be able to allocate system resources according to the type or class of the MSs. Since different types of MSs have different system resource and QoS requirements, different priority or preferential treatments may be given to different traffic services in such a way that the system resources could better be utilized.

When a MS moves from one cell into a different cell while a data transfer is in progress, a handoff mechanism is used to transfer the ongoing call to a new channel belonging to the new BS. In a IS-95 CDMA system, a unique handoff capability called soft handoff that cannot be supported with other wireless systems is provided. The universal frequency reuse makes soft handoff possible for a MS to receive and send the same message simultaneously from and to two different BSs. On the FL, the two BS signals

can be combined to improve performance, as with multipath combining. In fact, one could regard the second BS signal as a delayed version reflection of the first, generated and purposely, rather than as a delayed reflection of the first caused by the environment. On the RL, the two different BSs will normally decode the signals independently. Should they decode a given message differently, it will then be up to the mobile switching center (MSC) to arbitrate. Qualitatively, this feature provides a more reliable handoff between BSs as a MS moves from one base station to the adjacent one.

2.2 CDMA Cellular System Capacity

Evaluation of the CDMA FL capacity is a non-trivial issue mainly due to the fast power control, flexible power allocation and soft handoff. Furthermore, the large variation of possible services with different bit rates and quality requirement does not make the situation any easier. Therefore time-consuming system simulations that incorporate complex call handling protocols are usually required to obtain a figure for the FL capacity [5].

2.2.1 Capacity Definition

System capacity is defined as the largest number of users that can be handled by a system [6]. In a multimedia cellular system like cdma2000 systems, it translates into the maximum number of users of different combinations of various traffic services. In this study, the capacity is defined as the maximum Erlangs of Voice and Data traffic that can be supported while limiting the blocking probability to below a fixed value of 5%.

2.2.2 Benefits of Knowing Capacity of Mixed Service Systems

The rapid increase in wireless mobile applications and their demands for a high-speed multimedia communications stands in clear contrast to the rather limited radio resources that have been allocated in international agreements. Hence, an efficient Radio Resource Management (RRM) is of paramount importance due to these increasing demands [6].

Since power is a common radio resource for all users, multiplexing of traffic services of very different channel characteristics and QoS requirements can be achieved by managing the distribution of power, which is the main responsibility of a RRM. Before any RRM can efficiently manage and utilize the limited radio resource, the RRM must first know how to measure them.

In addition, the system may also need to know the effect that admitting a new MS may have on other existing and active MSs in the system. Hence, knowing the system capacity and others will provide important information for designing an effective RRM strategy and link budget which will safeguard the QoS of all active MSs in the system [7] and attempt to minimize the probability of false admission and false rejection [6].

By understanding how, for instance, the dominating nature of any particular traffic service may affect the existing MSs or overall system performance, the system can adaptively change admission criteria in the admission control strategy so that the common radio resources can be fully utilized. It is also important to know how a particular traffic service is being discriminated against when two different traffic services with distinct channel characteristics and QoS requirements are sharing a common radio resource.

2.3 Problem Formulation

Unlike the capacity in cellular systems using Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) technologies, the capacity in CDMA cellular system is known as soft capacity. Both FDMA and TDMA cellular systems are bandwidth-limited systems while CDMA cellular system is an interference-limited system. For bandwidth-limited systems, the total number of channels is deterministic while the total number of channels in an interference-limited system changes with the system loads. The number of MSs that a CDMA cellular system can support in the RL depends on total interference received by a BS and the number of MSs that a system can support on the FL depends on the interference received by a MS receiver. In other words, the system capacity changes with the channel conditions. Hence, Erlang B capacity formulas [8], which is derived and based on the bandwidth-limited system, cannot provide an accurate estimate on the capacity of an interference-limited and multi-rate system like cdma2000.

For applications where multimedia services need to be provided, there is a need for a better understanding of the nature of the relationships, between the QoS requirements of different traffic services in the system. Generally, Voice traffic models are well understood through many years of telephone experience and they are also well characterized by a Poisson arrival process and a usual holding time of few minutes, but the capacity of a truly integrated Voice and Data CDMA system is not clearly understood. Since Data traffic has a large dynamic range in transmission rates, statistical characteristics and QoS requirements, the capacity evaluation of a truly integrated Voice and Data CDMA system becomes quite difficult.

In cdma2000 systems, different traffic services have different channel and QoS requirements. A channel called the Supplemental Channel (SCH) is used to transport high data rate circuit or packet switched data traffic, while a pair of channels called Dedicated Control Channels (DCCHs) is used to transport control messages. For circuit voice traffic service, a pair of traffic channels called the Fundamental Channels (FCHs) is used to exchange the data and control messages between voice users and the BS.

Asymmetric traffic between the FL and the RL in the Internet web browse and data download applications is a realistic scenario. Usually, traffic load on the FL is much heavier than that on the RL because of the difference between the large sizes download WWW and ftp pages, which are carried over on the FL, and the user-initiated short request messages, which are carried over on the RL. Thus, a larger capacity on the FL is needed.

For these reasons, the primary objective of this study is to estimate the long term FL Erlang capacities of an integrated Voice and Data system based on cdma200 scheme. Moreover, when the FL channels are not perfectly orthogonal due to the effect of multipath, the FL capacity tends to drop as all MSs in the system will experience more co-channel interference from their serving cell. The effect that each service has on the system will also be evaluated.

2.4 Review of Prior Work

A book written by A. J. Viterbi [8] provided a complete description regarding the CDMA technology as well as a classical method to estimate capacity for homogeneous circuit switched traffic service for both the FL and the RL in CDMA systems. It becomes a

classic and important reference for people who want to understand the first developed CDMA cellular technology, i.e., IS-95. In [8][9][10], an outage condition based on the total received power was defined and Erlang capacity of a Voice-only CDMA system was computed. In those studies, capacity was defined as the maximum Erlangs of Voice traffic that can be supported while limiting the outage probability to below a fixed value of 1%. In [11], an analytical method for estimating the capacity of 3G Voice-only CDMA system based on wideband CDMA schemes was presented. Although only the FL was considered in this paper, it is possible to extend the method to analyze the RL as well.

Studies in [12][13][14] provided an analytical method for estimating the RL capacity of an integrated Voice and Data CDMA system based on the outage probability of the signal to interference ratio while [4][5][15] provided an analytical method for estimating the capacity on the FL. In [14], the study of [9] was extended to include Data service in the system. Calls of either type are blocked from the system when the outage probability exceeds a fixed outage probability threshold. In [16], a blocking probability was introduced as an additional grade of service metric in addition to the outage probability.

In [4][11][12][13][14][15][16], the Voice and Data traffic models were assumed to be identical in all aspects except the data rate, activity factor and SINR requirements. This particular assumption may have led [4][12][15] to conclude that the Voice and Data transmission threshold or the capacity curves in a heterogeneous system is almost linear, and its slope is approximately equal to the ratio of the bit rates and signal to interference ratios until a certain threshold was reached. This conclusion may even have led [12] to

suggest that the interference caused by a Data user is equivalent to an interference caused by k Voice users where the Data bit rate is k times greater than the Voice bit rate.

The effect that a Voice MS has on the overall system may not be the same as the effect of a Data MS, as shown in [17]. The underlying reason is that the Voice and Data traffic services have different channel characteristics in term of radio resource requirement. In addition, when the FL channels are not perfectly orthogonal, a MS of a given service will receive a different amount of co-channel interference compared to another mobile user of a different traffic service. On the other hand, interference caused by one MS from one service should not be assumed to be equivalent to the interference caused by a number of MSs from another service, simply based on the ratio of their bit rates and signal to interference ratios. By using the ratio of the intra-cell interference to inter-cell interference as a means to measure the outage probability as in [9][10][13][15], may not be useful to determine an approximated capacity for a mixed traffic model.

Furthermore, most traditional models are oversimplified and are unable to account for the full dynamic interactions among distinctive different traffic services and how the system discriminates among these services. For simplicity and analytical convenience, the cumulative multiple access interference is frequently modeled as Additive White Gaussian Noise (AWGN) or some other distributions in the traditional approach. For example, the total received FL interference is modeled as a Gaussian random variable in [15] or the average carrier signal to interference ratio of a MS is approximated as a lognormal distributed random variable in [4].

In addition, a call or session may be lost due to adverse propagation conditions caused by mobility or excessive interference. To include or mimic such phenomena in the capacity estimation would require detailed specification of call-handling protocols such as call admission control, power control, hard handoff controls, call dropping control and some others [6].

For these reasons, simulation becomes very appealing because it can mimic what happens in a real system or what is perceived for a real system that is in the design stage.

Complex call handling protocols such as power control, admission control, handoff controls and others can be implemented in the simulation. The dynamic interactions between any two traffic services and the resulting effects of these call-handling protocols can easily be observed. The observations from a simulation should and may very well directly correspond to the observations that could be recorded from the real system.

2.5 Capacity Estimation Through Simulation

Experiments can be performed using the software simulation much like experiments can be performed using hardware. System parameters such as mobile speed, activity factors and QoS requirements can easily be changed, and the impact of these changes can be evaluated. By changing the parameters, or even the system topology, “what if” scenarios can be played much more quickly and economically using a simulation than with a system realized in hardware. If it is used properly, simulation goes hand in hand with traditional techniques in that simulation can often be used to guide analysis [18].

Simulation, useful as it is, does have limitations [18]. It must be remembered that a system simulation is an approximation to the actual system under study. The nature of

the approximations must be understood if one is to have confidence in the simulation results. The accuracy of the simulation is limited by the accuracy to which the various components and subsystems within the system are modeled. It is often necessary to collect extensive experimental data to ensure that simulation models accurately reflect the behavior of the real systems. Another limitation of simulation lies in the excessive computer run time that is often necessary for estimating performance parameters.

Since the objective of this simulation study is to evaluate the long-term system Erlang capacity and the resulting effects of supporting mixed traffic services, the steady state behavior of the simulator will be studied. Hence, we need to establish when the simulation is running at steady state.

Although the final results of a steady state simulation is not influenced by the initial conditions, these initial conditions should be chosen very carefully hoping that these initial conditions will drive the simulation to achieve their steady state quickly.

This study presents a simulation strategy to estimate the steady state or long term Erlang capacity of the integrated Voice and Data service on the FL. The effect of different degree of FL channel orthogonality on those Erlang capacities is also presented. An extensive evaluation concerning the effect that each service has on the system capacities and operations will be discussed as well.

An existing SimScriptII.5-based Wideband CDMA Network Simulator (W-CNS) [19] [24] is used to model the operation of a multi-rate and multi-cell cdma2000 based cellular system. In order to mimic the real system as much as possible, a distributed admission control that maintains stability of the system in term of power resource management is

used. In addition, handoff and power controls are implemented to provide seamless service for all MSs while maintaining their QoS requirements. Other call handling protocols such as call dropping control and initial power allocation are also included to accommodate traffic services of different channel characteristics and QoS requirements.

In order to investigate how different FL orthogonality factors can affect the system capacity and performance, the receivers at all MSs are assumed to have experienced a fraction of co-channel interference from the serving cell. Samples in term of blocking probability, system capacity, total FL transmitted power and initial power required by MSs will be monitored. The blocking probability will be used to measure the offered load of the system while the total FL transmitted power and initial power required will be used to evaluate the effects of each service have on the system.

The design details of the system modeling and call handling protocols such as admission control, handoff control, power control, call dropping control and others are explained in the next two chapters followed by the details of the steady state simulation strategy.

3 System Modeling

This chapter explains how the system is modeled for the purpose of the simulation.

Details about the high level design such as simulation plane, common control channels, dedicated control channels, traffic channels and their properties are described here. Low level design details such as the computation of bit energy or received signal strengths, Pilot signal strengths, etc. will be explained in the second half of this chapter.

A simulator called CDMA Network Simulator (CNS) which models IS-95 system has been developed by [19][24]. CNS, which supports Voice only service, was upgraded to support Circuit Switched Data service with a bandwidth of 5Mhz (3.6864Mcps). The simulator was then called Wideband CDMA Network Simulator (W-CNS). This time-driven CNS simulator was originally developed to study system planning, performance assessment and has been used to carry out CDMA radio resources evaluation. The W-CNS simulator uses a simplified wideband DS-CDMA system model, and provides a foundation for investigating some call handling procedures, system capacity and performance of mixed traffic services on the proposed 3rd generation wireless cdma2000 systems. It is used to assess the impact of proposed concepts and algorithms for combinations of mixed traffic, to evaluate the system performance, and to provide information to support design and for further improvement. The system is able to support both voice and variable-rate stream data traffic in vehicular, pedestrian and indoor environments.

3.1 Simulation Plane

A simulation plane specifies a service coverage area. The simulation plane consists of a total of 7 equal-sized omni-hexagonal cells, as shown in Figure 1. The actual simulation plane is a circular simulation plane. However, every MS is generated within one of the hexagonal cell and the MS is free to move within the circular simulation plane. In this uniform cell deployment, each cell is equipped with a Base Station (BS) transceiver and an antenna 50m above the ground. The antenna has a gain of 9 dBi, and cabling to the BS gives a 2.5dB loss.

Figure 1: Simulation Plane

When a MS is generated, it is put on the simulation plane. The call attributes such as location, speed, direction, data rate, etc. are used for setting up newly arrived MS calls. The MS could be either Voice or Data source. MSs could also be moving with different speeds and in different directions. In order to simulate mobility, the location of the MS is

updated every 0.5 seconds. Since the location of the MS changes, the received signal strength changes as well as the received interference. Hence, power control and other call handling procedures that mimic what happens in a real system are performed every 0.5 seconds to provide a seamless service to every MS in the system.

The center-cell is the cell-of-interest. All statistics are collected from the cell-of-interest as the 1st-tier cells have suffered the so-called edge effect. A MS (Voice or Data MS) is generated uniformly within the equally-size hexagon cell boundary. It is assumed that a MS is allowed to send only one admission request to a BS which has the strongest received Pilot signal strength. If the admission request is rejected due to unavailability of power resources of the target BS, i.e., the call is "blocked", and the MS will be eliminated from the system and returned to the population, i.e., retries are not allowed.

Each cell has 2 types of traffic channels namely Fundamental Channels (FCHs) and Supplemental Channels (SCHs). It also has a Dedicated Control Channel (DCCH) for every Data MSs. There are three types of common control channels: one Pilot Channel (PICH), one Synchronization Channel (SYNCH) and one Paging Channel (PCH) (all are in the FL). It is assumed that each cell has enough number of FL FCH, DCCH and SCH. Functionality of PICH, SYNCH, and PCH is the same as the IS-95 system. FCHs carry circuit-switched voice traffic while SCHs carry circuit-switched data traffic.

A chip rate of 3.6864Mcps (a bandwidth of 5 MHz CDMA channel in the 2 GHz band) is selected. Chip rate determines the degree of spreading for the CDMA signal and thus the processing gain for the CDMA signal. In IS-95, standard band utilizes 1.2288Mcps as the chip rate, resulting in a bandwidth of slightly smaller than 1.25MHz. For the

proposed cdma2000 systems, a chip rate of 3.6864 Mcps ($3 \times 1.2288 \text{ Mcps}$) has been specified for a variety of reasons. For example, it allows a greater backward compatibility with the existing IS-95 systems and it fits well into the 5MHz band allocation [25].

When the simulator generates a MS location, a cell setup process takes place. It is assumed that the BS estimates the total power needed by the new MS in order to support its initial SINR or bit energy to interference density ratio (E_b / I_o). The BS uses this initial power requirement to determine if an admission can be granted to this MS. If the MS is accepted, a traffic channel and a dedicated control channel, if it is a Data MS, are assigned and the MS begins to move freely on the simulation plane. The MS then begins to measure its own SINR, perform power control and monitor call-drop conditions and others, every 0.5 seconds. Necessary actions are taken whenever a condition is met, and the statistics are collected accordingly.

The W-CNS attempts to simulate the behavior of a proposed cdma2000 communication system and generate a number of statistics that describe the performance of the system. In particular, the W-CNS will be used to provide information on the critical issues of system capacity due to different combinations of traffic services and imperfect orthogonality of the FL channels.

3.2 Propagation Model

A Hata propagation model is used in this study's simulator [19]:

$$L_p[dB] = -(120.5 - 20\log(H_s) + 1.9\log(H_s^2)) - (36.6 - 1.9\log(H_s)) \cdot \log(R) \quad (1)$$

where L_p = path loss,

R = distance in km between the MS and BS,

H_s = height of the BS antenna in m (assumed 50m).

A distance correlated shadow loss is used. Distance correlated shadow loss sample has a memory of the last sample, weighted by a function of the covered distance. If the MS is static, then the shadow sample is equal the last one generated.

$$SL_{n+1}[dB] = b \cdot SL_n + \sqrt{1-b^2} \cdot \mu_{n+1} \quad (2)$$

where SL_n = Correlated shadow loss sample took in the last distance update;

SL_{n+1} = Correlated shadow loss sample after a distance Δd has been covered;

μ_{n+1} = sample of a lognormal distributed random variable of zero-mean and 6dB standard deviation;

$$b = \exp(-\frac{\Delta d}{d});$$

Δd = distance covered since the last sample was generated (in km);

d = constant, defined in the scenario of simulation (typically $d = 0.1\text{km}$).

Thus, a complete path loss, L_j , including distance correlated shadowing between a BS j and a MS is shown in Eq. (3):

$$L_j = L_p + SL . \quad (3)$$

3.3 Common Control Channels

Only some common channels are simulated. There are one Pilot Channel (PICH), one Synchronous Channel (SYNCH) and one Paging Channel (PCH) per cell. SYNCH and PCH are considered dummy channels, as their actual functionality is not simulated. They not only deprive some FL power resource but also create some interference to the MSs. The most important common control channel of all is the Pilot Channels. The Pilot signal strengths of all BSs in the system will be used for the purposes of admission controls, handoff controls, etc. The computation of the Pilot Signal Strengths will be shown later in this chapter. Some of the usages of Pilot signal strengths in some call handling procedures are described in the next chapter.

3.4 Traffic and Dedicated Control Channels

Traffic channels in this simulator are categorized into Fundamental Channels (FCHs) and Supplemental Channels (SCHs). FCHs are used for voice message and signaling while SCHs are primarily used for data transfer. The Dedicated Control Channels (DCCH) carry all signaling information for the Data MSs.

FCHs and DCCHs are inherently identical except they may have different data rates and activity factors. FCHs and DCCHs are equivalent to an existing IS-95 traffic channel.

Their behavior of call setup, power control and handoff are the same as in IS-95. SCHs are introduced for high rate Circuit or Packet switched data traffic services. All traffic and dedicated control channels are subjected to interference. Some properties of these traffic and dedicated control channels are listed in Table 1.

Table 1: Some Properties of the Traffic and Dedicated Control Channels

Service	Channel	Data Rate (kbps)	Handoff		Activity factor	Target Eb/lo
			Hard	Soft		
Voice	FCH	9.6		√	40%	5.5dB
Circuit Data	DCCH	4.8		√	100%	5.5dB
Circuit Data	SCH	144	√		100%	5.5dB

3.4.1 Supplemental Channel (SCH)

SCHs are used solely for Data traffic transmission while DCCHs are used to assist this Data MS in signaling. The transmission rate is constant, therefore a rate detection is not required. Only circuit-switched data is supported. SCHs suit for high-rate data transfer service. Only one communication link of SCH is allowed for each and every Data MS and SCHs are unidirectional, i.e., they do not come in pairs (RL and FL). Only Hard Handoff is performed for SCHs

3.4.2 Fundamental Channels (FCH)

FCHs are used primary for Voice traffic transmission. Whenever a Voice MS issues an admission (new call or active call in soft handoff processing) request to its target BS, it is assumed that a pair of FCHs will be assigned to this Voice MS. Since this study only focuses on the FL, it is assumed that there is no limitation or constraint on the RL. It is further assumed that all Voice MSs use FCHs to transfer messages as well as control information to or from their respective BSs.

3.4.3 Dedicated Control Channels (DCCH)

DCCHs are used primary for signaling. They always come in pairs with a single SCH. Whenever a Data MS issues an admission (new call or active call in soft handoff) request to its target BS, it is assumed that a pair of DCCH will be assigned to this Data MS. It is assumed that Data MSs are using their DCCH to communicate with their serving BSs while using their SCH solely for data transfer. In this study, it is assumed that SINR of DCCHs should be kept above its outage threshold in order to keep the communication link between BS and MS active. If the SINR of SCH falls below its outage threshold, BER of the message will increase and the message received may or may not be retrievable. However, the MS may still receive control information on its DCCHs provided that the DCCHs do not suffer any outage. If a MS suffers outage (either on SCH or DCCHs) for some time, this communication link of this MS-BS will be dropped to avoid unnecessary interference to other MSs and serve no benefit this MS in trouble.

3.5 Traffic Model

For this study, it is assumed that there are two types of traffic services: Voice traffic (Voice) and Stream Data or Circuit Switched Data traffic (Data). Two independent Poisson processes are used to model the arrival of Voice MSs and Data MSs separately. How often a new MS comes into the system is controlled by the rate parameter, λ . Voice MS arrival rate or Voice traffic load is denoted as λ_v while Data MS arrival rate or Data traffic load is denoted as λ_D . Both traffic services have an average call duration (or call holding time) of 120 seconds.

For Voice services, a 40% activity factor is used in this model. An ON-OFF mode of the Voice service was not simulated. The activity factor is used primary for the interference computations, i.e., only 40% of the total power allocated to this MS is effective. For Data traffic service, the traffic model is a constant bit rate model, with 100% of activity factor, i.e., Data MS will occupy the both a SCH and up to 3 DCCHs over the duration of the calls.

3.6 Pilot Channel

Once a MS (Voice or Data) enters a system, it uses its searcher to locate and measure the Pilot signal strengths (E_c/I_o) of all BSs in the system. These Pilot signal strengths will then be ranked and used for the purposes of admission control, handoff controls, power controls, etc.

3.6.1 Pilot Signal Strength (E_c/I_o) Computation

The received Pilot Signal strengths by a MS from a given BS i , $(E_c/I_o)_i$, is calculated as follows:

$$\left(\frac{E_c}{I_o} \right)_i = \frac{S_i^{PICH}}{N_o W + \zeta_i \cdot S_i^T + \sum_{j=1, j \neq i}^M S_j^T} \quad (4)$$

where

$$S_i^{PICH} = P_i^{PICH} \cdot \Phi_i, \quad (5)$$

$$S_j^T = \left(P_j^{PICH} + P_j^{SYNCH} + P_j^{PCH} + v_f^{F-FCH} \cdot \sum_{k=1}^{N_j^{FCH}} P_{k,j}^{FCH} + \sum_{k=1}^{N_j^{DCCH}} P_{k,j}^{DCCH} + \sum_{k=1}^{N_j^{SCH}} P_{k,j}^{SCH} \right) \cdot \Phi_j \quad (6)$$

and
$$\Phi_k = L_k \cdot G_{BS_k} \cdot G_{MS} \quad (7)$$

where W is the spreading bandwidth (3.6864Mcps), N_o is the thermal noise density including the MS noise figure, S_i^{PICH} is the received Pilot power from the BS i at MS's receiver input, S_j^T is the total received power from the BS j . ζ_i is the FL orthogonality factor. $P_{k,j}^{FCH}$, $P_{k,j}^{DCCH}$, $P_{k,j}^{SCH}$ are the full rate power allocated to FCH, DCCH and SCH, of MS k by BS j , respectively. $P_{k,j}^{PICH}$, $P_{k,j}^{SYNCH}$, $P_{k,j}^{PCH}$ are the power allocated to Pilot Channel, Sync Channel and Paging Channel of BS j , respectively. v_f^{F-FCH} is the activity factor for the FL FCH. Note that the activity factors of SCHs and DCCHs are always 100%, i.e., v_f^{F-SCH} and v_f^{F-DCCH} are equal to 1 and thus not shown in Eq.(6). N_j^{FCH} , N_j^{DCCH} , N_j^{SCH} are the total number of FCHs, DCCHs and SCHs currently in used at BS j , respectively. G_{BS_j} and G_{MS} are the antenna gains (including cable loss) for BS j and the MS, respectively. Finally, L_j is the path loss between BS j and the MS including shadowing (see section 3.2). $S_i^{T'}$ is the total received power from BS i excluding the received full rate traffic power from the MS i , i.e., $S_i^{T'} = S_i^T - S_i^{channel}$, where $channel \in \{FCH, DCCH, SCH\}$.

3.6.2 Pilot Sets

It is assumed that each MS has a “searcher”. It is a receiver dedicated to search for pilots and assist in the admission and handoff controls. The MS tunes the searcher for a Pilot pseudonoise offset and measures its accumulated energy. The MS searches and detects

the presence of any strong pilots. At any time, the MS will be aware of the status of all possible pilots on its current CDMA frequency. It then classifies these pilots into 2 Pilot sets¹:

1. Active Set: pilots associated with FL traffic channels assigned to the MS, and
2. Candidate Set: all other pilots that are not in the Active Set.

The MS computes the received Pilot Signal Strength, E_c/I_o . When E_c/I_o exceeds an add threshold called T_{ADD} or falls below a drop threshold called T_{DROP} , the MS reports the results to BS via Pilot Strength Measurement Message on the RL. Thresholds T_{ADD} and T_{DROP} are used to decide which pilots are added to or removed from the Active Set. BS may decide if handoff (Hard or Soft Handoffs) is required. In other words, that Pilot Strength Measurement Message could trigger a handoff. Each and every MS maintains the 2 Pilot sets while every Data MS keeps an extra Pilot set called Packet Active Set. Every MS measures and ranks these pilot signal strengths every 0.5 seconds before any power control, handoff control, etc. is processed.

First, the received pilot signal strengths are measured for admission control purpose.

Once a MS is admitted to the system, E_c/I_o of all BS in the systems are then measured and ranked in the Pilot sets. The Candidate Set of a MS is updated first, followed by the Active Set. Packet Active Set is updated last. The numbers of entry in the Active Set and Packet Active Set represent the number of communication links a MS has in the system. If a MS has 3 entries in its Active Set, it means that the MS is currently in Soft

¹ IS-95 has 4 Pilot sets: Active, Candidate, Neighboring and Remaining sets

Handoff and has communications links with up to 3 separate BSs. Similarly, Packet Active Set has only one entry and every Data MS is only allowed to have one SCH. The sole entry in PAS must also be an entry in the MS's Active Set. If the current serving BS is no longer in the Packet Active Set after the Active and Candidate Sets are updated, the system will immediately attempt to hard handoff the current SCH to a target BS that has the highest pilot signal strength in the Active Set. Intuitively, the target BS has to be an entry of the Active Set. If the hard handoff fails, the Data MS will be dropped immediately. If the hard handoff is successful, the attributes of the Data MS are updated and the new serving BS will be the target BS and the target BS will be the sole entry in Packet Active Set.

Figure 2, on page 29, illustrates the messages exchanged and how the Pilot sets are updated during a typical handoff process.

1. Pilot strength of BS₂ exceeds T_{ADD} . MS sends a Pilot Strength Measurement Message.
2. BS₁ sends a Handoff Direction Message to MS. MS transfers pilot of BS₂ to the Active Set.
3. Pilot strength of BS₂ is higher than pilot strength of BS₁. MS starts the handoff drop timer.
4. Handoff drop timer expires. MS sends a Pilot Strength Measurement Message.
5. BS sends a Handoff Direction Message. MS replaces BS₁ in the Packet Active Set with BS₂.
6. Pilot strength of BS₁ drops below T_{DROP} . MS starts the handoff drop timer.
7. Pilot strength of BS₁ exceeds T_{DROP} . MS resets and disables the handoff drop timer.
8. Pilot strength of BS₁ drops below T_{DROP} . MS starts the handoff drop timer.
9. Handoff drop timer expires. MS sends a Pilot Strength Measurement Message.
10. BS sends a Handoff Direction Message. MS moves pilot of BS₁ from the Active Set to the Neighbor Set.

Figure 2: Messages Exchanged of a Typical Handoff Process

3.7 Forward Link SINR or Eb/Io

Received bit energy to interference ratio (E_b/I_o) is also called as the signal-to-interference-plus-noise ratio (SINR). It is assumed that the bit error rate (BER) is a function of E_b/I_o calculated at the output of the despreader, where E_b is the energy per bit and I_o is the effective interference density (noise and co-channel interference). It is the signal strength after the received signal is despread. The definition of FL SINR is slightly different between SCH and DCCH/FCH. In this study, there is exactly one communication link between a BS and a MS for SCH. Whereas, a MS could have between 1 to 3 simultaneous communication links via 3 DCCHs or FCHs with 1, 2 or 3 different BSs due to Soft Handoff. The received SINR of the DCCH or FCH for this MS is also called “joint E_b/I_o ”.

The formula to measure the received full rate E_b/I_o of SCH at a given MS is shown in Eq.(8). The joint E_b/I_o of the DCCHs or FCHs at a given MS are shown in Eq.(9), Eq.(10), respectively.

$$\left(\frac{E_b}{I_o} \right)^{SCH} = \frac{S_i^{SCH}}{N_o W + \sum_{\substack{j=1, \\ j \neq i}}^M S_j^T + \zeta_i \cdot S_i^{T'}} \cdot \frac{W}{R_b}, \quad (8)$$

$$\left(\frac{E_b}{I_o} \right)^{DCCH} = \sum_{i=1}^W \frac{S_i^{DCCH}}{N_o W + \sum_{\substack{j=1, \\ j \neq i}}^M S_j^T + \zeta_i \cdot S_i^{T'}} \cdot \frac{W}{R_b}, \quad (9)$$

$$\left(\frac{E_b}{I_o}\right)^{FCH} = \sum_{i=1}^{\psi} \frac{S_i^{FCH}}{N_o W + \sum_{\substack{j=1, \\ j \neq i}}^M S_j^T + \zeta_i \cdot S_i^{T'}} \cdot \frac{W}{R_b}, \quad (10)$$

where $S_i^{T'}$ is the total received power from BS i excluding the received traffic power, i.e., $S_i^{T'} = S_i^T - S_i^{channel}$, where $channel \in \{FCH, DCCH, SCH\}$. Note that the DCCH suffers the same-cell co-channel interference including the transmitted power allocated to the SCH of the same Data MS and vice versa. $S_i^{channel} = P_i^{channel} L_i G_i G_{MS}$ is the received traffic power from BS i at MS, $P_i^{channel}$ is the transmitted traffic (either Voice or Data traffic) power from BS i . W is the spreading bandwidth while R_b is the data rate, W / R_b is the processing gain, and ψ is the number of the BSs involved in Soft Handoff.

The processing gains for SCH, FCH and DCCH are 25.6, 384 and 768, respectively. When the data rate demands changes, the processing gain changes accordingly. Thus, for a higher data rate MS, its processing gain is lower than those of a lower data rate MS. Therefore, a high data rate Data MS needs a higher power allocation for the same QoS as a lower data rate Voice MS. Each service has its own QoS figure determined by its required SINR which in term corresponds to its bit error rate (BER).

3.8 QoS and GoS

Grade of Service (GoS) is defined as the probability of a call being blocked or delayed more than a specified interval.

Quality of Service (QoS) is defined as the performance specification of a communications channel or system. QoS may be quantitatively indicated by channel or system performance parameters, such as SINR, BER, block error rate, frame error rate, message throughput rate, call blocking probability, etc.

The QoS of a MS is measured in the received SINR or E_b/I_o . In this study, the target E_b/I_o of each traffic channel (SCH, DCCH or FCH) is 5.5dB [26] with a minimum of 4.5dB. It is assumed that the BER requirement is met if the received E_b/I_o is greater than or equal to 4.5dB. However, in order to prevent unnecessary interference, the maximum received E_b/I_o is set to 6.5 dB. Thus, no power adjustment is needed if the received E_b/I_o falls between 4.5-6.5 dB [19][24]. Intuitively, a E_b/I_o of more than 6.5 dB gives the MS a lower BER. However, it also creates a larger and unnecessary interference to other MSs in the system and may over-occupy the system power resource. The system not only should keep the average E_b/I_o of all MSs within 1 dB from the target value, it should also maintain the outage probability to the minimum.

3.8.1 Outage Probability

Outage probability is defined as the probability of failing to achieve adequate reception of signal due to high BER or low (joint) E_b/I_o .

In this study, the outage probability is defined as the probability of E_b/I_o samples of SCH or joint E_b/I_o samples of DCCH/FCH falls below 4.5 dB. If a MS is in outage, the BER is assumed to have exceeded the desirable level. When a MS is in outage, Closed

Loop Power Control (CLPC) will be performed to increase the power allocation to this channel.

When the average of 8 consecutive (or 4 consecutive seconds) E_b/I_o samples of SCH or joint E_b/I_o samples of DCCH/FCH is lower than 3.0 dB [19][24], the corresponding communication link will be disconnected (see also section 4.4). Hence, a Data call could be dropped either due to unsustainable E_b/I_o of its DCCH or SCH. For Voice MS, the call could be dropped due to unsustainable E_b/I_o of its FCH. Since all E_b/I_o samples are collected right after the power control, if the received signal strength of a MS doesn't increase after the CLPC, it is intuitive to assume that serving BS doesn't have enough power to sustain this MS power (or power increment due to power control). Moreover, if the QoS of this channel fails to recover after 8 consecutive power control circles, this traffic channel should be dropped to prevent the MS from clinging to the system power resources and causing more interference to other MSs in the systems while no message has been successfully received.

3.8.2 Blocking Probability

The blocking probability is defined as the probability that an admission request by the newly generated MS is blocked or rejected due to unavailability of power resources at the target BS to support MS's initial SINR or E_b/I_o requirement. Once an admission request is rejected, it is assumed that the MS will not make another admission request to another BS (retries are not allowed). This MS will then be terminated immediately.

Probability of blocking is an important point estimator in our steady state simulation (see also section 5.4). It is used to determine if the simulation is running at steady state. Its variations are used to construct the confidence interval, which in turn is used to determine if the simulation is indeed running at steady state. It is also used to determine if the combinations of traffic loads produce a desired level of service coverage, i.e., the probability of blocking is often used to measure GoS of a system.

3.9 Co-Channel Interference

On the FL, all MSs served by all BSs in a system use the same carrier frequency band the signals received at the MS from neighboring BSs are asynchronous. Hence, once the FL signal of each communication link between a BS and a MS crosses the boundary of the cell, it reaches all other MSs of all other BSs in the form of (inter-cell) co-channel interference.

If it is possible to control the relative timing of transmitted signals, the transmitted signals can be made perfectly orthogonal. However, if the signal is dispersed due to multipath fading², the FL channel orthogonality begins to diminish. Once it happens, the FL signals of all communication links between all other MSs of the same cell and the serving BS also reach the MS in the form of same-cell co-channel interference. Since the extra same-cell co-channel interference will lower the MS's SINR, the MS's will require a

² the main factors that have largest effects on the multipath fading are differential delay, the amount of Doppler shift due to mobility, etc.

higher FL power allocation. Thus, the effect of the FL orthogonality factor plays quite an important role on the FL capacity [27].

In this study, the level of same-cell co-channel interference reaches the MS is represented as a percentage of the total FL transmitted power, denoted as ζ_i (FL orthogonality factor). If the FL channels are perfectly orthogonal, ζ_i is set to zero. If the FL channels are asynchronous, ζ_i is set to 1. In order to examine the effect of imperfect FL channel orthogonality on the FL capacity, 4 different sets of simulations are performed using 4 different ζ_i values (0.0, 0.2, 0.8, 1.0).

4 Call Handling Procedures

This chapter explains some important call-handling procedures that may impact the capacity estimation. For each procedure, a brief definition is given followed by a detailed explanation of how it was implemented in the simulator. The impact that this call-handling procedure has on the system capacity as well as underlying assumptions made will be discussed.

4.1 Admission Control

In a power controlled DS-CDMA system, FL transmitted power is regulated to provide each MS with an acceptable connection by limiting interference caused by other MSs. In these systems, the number of MSs that each cell can support is limited by the total co-channel interference received at each MS and will vary with time. When a system is congested, admitting a new MS can only degrade the communication link quality for ongoing active calls and may eventually lead to call droppings. Thus, an admission control is needed to control the number of MSs the system should grant access to. In other words, an admission control is used to utilize the system resources not only to achieve high capacity, but also to maintain system stability.

In a system that supports mixed traffic services, an effective admission control algorithm should allocate system resources according to the type or class of the MSs. Since different type of MSs have different system resource and QoS requirements, the system should account for those differences when allocating resources. This point of view makes the resource allocation a multi-dimensional optimization problem [17].

If an admission control is too protective or tight, the QoS of the admitted MSs may somewhat be guaranteed at the expense of admitting fewer MSs in the system (i.e. high probability of blocking and lower system resource utilization). However, if the admission control is too loose, the utilization of system resources may be maximized at the expense of degrading QoS of the admitted MSs. Therefore, an effective admission control may have to make a trade off between the QoS of different traffic types and utilization of the shared and limited system resources.

In this study, a very simple admission control that is based on a fixed maximum transmitted power is implemented. This admission control prevents all BSs from transmitting above their maximum allowable limit. When the maximum power is reached, new calls are blocked. An estimated initial power is used as a decision criterion if an admission should be granted. The basic strategy of this study's admission control is to make sure that the target BS is able to allocate enough power resource to support the initial SINR of the new MS.

Once the target BS receives an admission request, it will attempt to estimate the initial power required by this MS (see section 4.2 for further details). The target BS will then check if the sum of the current total transmitted power and the estimated initial power required by this new MS exceeds the maximum allowed transmitted power. If it does, the admission request will be rejected. This MS will then be erased from the system. Otherwise, the admission request is accepted and the target BS becomes the MS's home BS or serving BS. The same amount of estimated initial power will be allocated to the MS. Once the MS is admitted, a FL DCCH and a FL SCH are allocated to this new MS

if it is a Data MS or one FL FCH is allocated if it is a Voice MS. Attributes are set and the newly admitted MS will then roam freely within the simulation plane. Some call handling and monitoring processes such as Power Control, Soft and Hard Handoff Controls, Call Dropping Control, etc. are activated. Call statistics are collected as well.

An admission request can be originated not only from a new MS, but also from an active MS that is in the process of being handed over. The following 2 sections describe in detail how a newly arrived MS and an active MS are treated by the admission control.

4.1.1 New Call Admission Control

Right after a new MS is generated, the MS will measure the Pilot signal strengths, E_c/I_o , of all BSs in the system. It will then send an admission request message to the BS (target BS) that has the highest Pilot signal strength received at the MS. Once the target BS receives the admission request, it will make a decision based on the current total transmitted power and the estimated initial power required by the new MS. Since a Data MS requires a DCCH and a SCH, the total initial power required by such Data MS will likely be significantly higher than a Voice under the same circumstances. Hence, the chances of blocking a Data MS are also significantly higher than blocking a Voice MS. If a new MS (Data or Voice) fails to obtain an admission for the first time, this MS will be “blocked” and removed from the system.

4.1.2 Active Call Admission Control

Unlike a new MS, an active MS usually requests only for a SCH or a FCH/DCCH when it is forced to perform a Hard or Soft Handoff, respectively. An active call may make an admission request to a target BS for a FCH for an active Voice currently on SHO or a

DCCH or a SCH for a Data MS currently on SHO or HHO, respectively (see section 4.3 for details):

1. A FCH for an active Voice connection currently in a SHO;
2. A DCCH for a Data MS currently in a SHO;
3. A SCH for a Data MS involved in a HHO.

If the MS fails a FCH/DCCH SHO, the MS may have to re-attempt the SHO in the next simulation update cycle (0.5sec) later. If the MS fails a SCH HHO, the MS may be forced to drop the call. The procedure is explained in more detail in section 4.3.1.

4.2 Initial Power Assignment/Measurement

Since the CDMA system is an interference-limited system, admitting a new MS increases co-channel interference to all existing and active MSs. Hence, a BS should be aware of the consequences if it accepts a new MS or an active MS in a handoff. However, knowing these consequences is not easy. Hence, the admission control used in this study is to simply maintain the total FL transmitted power of each and every BS in the system. As described in section 4.1, the BSs make their admission decision based on the estimated initial power required by the MS.

Since it is very difficult to accurately measure the actual power required for a new or active MS, the initial power required is estimated, and since these estimates are not accurate, false admissions and false rejections occur with certain probability. If the initial power needed by a MS is overestimated, the blocking probability tends to be higher. If the initial power is underestimated, the allocated power may not be enough to sustain the

SINR of this MS. This MS may eventually suffer a high outage probability and eventually be forced to drop the call. In this study's simulator, the initial power is assumed to be perfectly estimated. The estimated initial power would be exactly the same amount of power a BS needs to allocate to this MS in order that the target QoS is met. In other words, the simulator used in this study ignores the possibilities of false admissions and rejections.

If a MS, which is currently in the system and has an active communication link with at least one BS, requests additional channels, its request may be denied. The rejection depends on the type of channel the MS is requesting. If the request is for a FCH/DCCH (i.e., the MS is attempting to have a 2- or 3-way SHO) is blocked, this MS will come back later to re-request a new FCH/DCCH in the next simulation update cycle. If the channel requested is a SCH, i.e., the MS needs to HHO the SCH to another BS, then this MS will be dropped if the HHO request is rejected.

An admission request will be accepted if the Inequality (11) is met:

$$P_{init} + P_i \leq P_i^{MAX} \quad (11)$$

where P_i^{MAX} = Maximum transmitted power allowable of BS i ;

P_i = Current total FL transmitted power of BS i ;

P_{init} = Total estimated initial power required by the MS.

The target BS will attempt to estimate the total initial power required by a Data MS to support both a SCH and a DCCH. The total initial power required by a Data MS is the

sum of initial power required to support one SCH and one DCCH on the FL as shown in Eq. (12). However, the total initial power required by a Voice MS is simply the initial power required to support one FCH as shown in Eq. (13).

For a Data MS:
$$P_{init} = P_{init}^{SCH} + P_{init}^{DCCH} \quad (12)$$

For a Voice MS:
$$P_{init} = P_{init}^{FCH} \quad (13)$$

In order for the target BS to accurately estimate the initial power requirement, the following assumptions are made:

1. The target BS extracts the channel estimation from the Pilot Measurement Report Message sent by the MS on the assumed error-free RL;
2. FL and RL have the same path loss;
3. initial SINR of 5.5dB for each and every channel (ch) is required.

The target BS can then estimate the initial power, P_{init}^{ch} , required to support channel ch as shown in Eq. (14).

$$P_{init}^{ch} = \left(\frac{1}{L \cdot G_{BS_i} \cdot G_{MS} \cdot P_g^{ch}} \right) \cdot \left(N_o W + \sum_{j=1, j \neq i}^M S_j^T + \zeta_i \cdot S_i^T \right) \cdot \left(\frac{E_b}{I_o} \right)_{Desired}^{ch} \quad (14)$$

where

$$\left(\frac{1}{L \cdot G_{BS_i} \cdot G_{MS} \cdot P_g^{ch}} \right) = \text{Inverse of product of path loss, BS and MS antenna gains, processing gain on the FL } ch;$$

$$\left(N_o W + \sum_{j=1, j \neq i}^M S_j^T + \zeta_i \cdot S_i^T \right) = \text{FL co-channel interference received at MS};$$

$$\left(\frac{E_b}{I_o} \right)_{Desired}^{ch} = \text{The initial desired } E_b / I_o \text{ for channel } ch \text{ and it is set to } 5.5\text{dB};$$

and $ch = \{\text{SCH, DCCH, FCH}\}.$

Definitions of all other terms used in Eq. (14) can be found in Section 3.7.

4.3 Handoff

Handoff is a process whereby a MS, which is served by a BS, is transferred to another BS. The main objective of a handoff is to provide a seamless service to every MS in the system so that the communication links are not disrupted when a MS roams from one cell to another cell. The handoff is normally triggered by some mechanism, which is related to the received Pilot signal strength, call quality or system loading.

There are two main types of handoffs, namely Hard Handoff (HHO) and Soft Handoff (SHO). A HHO is sometime called “break before make”, while a SHO is called “make before break”. When a MS is in a HHO, the MS is required to disconnect the present communication link before a new communication link can be made. Whereas, a MS that receives signals from more than one BS is said to be in a SHO. In this study, a MS can have up to 3-way SHO. FCHs and DCCHs can have a 1-way, 2-way or even 3-way SHO, while a SCH can only have HHO.

Every active MS (both Voice and Data) constantly measures and ranks the average received Pilot signal strengths of all BS in the system. The MS then reports the Pilot

signal strength measurement back to its serving BS. The network will then decide if a SHO and/or a HHO is needed in order to provide a seamless service to the MS.

4.3.1 Hard Handoff (HHO)

There are two conditions required to initiate a HHO on the SCH. The first condition is triggered when the serving BS's SCH has been removed from the newly updated Active Set. In this case, the current serving BS (owner of MS's SCH) no longer belongs to the Active Set, and the received Pilot signal strengths of 3 other neighboring BSs are higher than the received Pilot signal strength of the current serving BS. Hence, the MS must hard handoff its current SCH to one of the BSs in the updated Active Set that has the highest Pilot signal strength (E_c/I_o).

The second condition is triggered when the received Pilot signal strengths of the other 2 BSs within the same Active Set are stronger than the received Pilot signal strength of the current serving BS for 4 consecutive power control cycles [19][24]. In other words, the average of the received Pilot signal strength of the serving BS begins to deteriorate and the communication links between the serving BS and the MS are in jeopardy. The BS will immediately attempt a HHO on the SCH to a BS that has the highest Pilot signal strength received at the MS.

Figure 3, on page 44, depicts the process of a HHO of a SCH. It is assumed that all BS-1, -2 and -3 belong to the Active Set, while BS-2 is the sole entry of Packet Active Set.

Figure 3(a) shows that the MS is using a SCH belonging to BS-2, which has the highest Pilot signal strength received at the Data MS. Figure 3(b) shows that as the MS moves, the Pilot signal strength of BS-1 becomes stronger than those of BS-2. A HHO is

initiated and the SCH is disconnected and relinquished to BS-2. Figure 3(c) shows that a SCH is allocated to the MS by BS-1. DCCHs are not shown in these figures.

Figure 3: A Typical Hard handoff (HHO) Process

If the BS of the best Pilot signal strength is unable to support the SCH, the HHO attempt is considered to have failed and the Data MS will be dropped from the system immediately.

4.3.2 Soft Handoff (SHO)

The interference problem that arises at cell boundaries where the MS is within range of two or more BSs can be turned into an advantage through a unique handoff mechanism called Soft Handoff (SHO). In IS-95 CDMA systems, the SHO is introduced to transfer calls within the same CDMA frequency band. On the FL, the MS can combine the received signals from two or more different BSs to achieve some gain from the site diversity in order to improve reception and ultimately the quality of the communication links.

A SHO eliminates the “ping pong” effect, where a MS is handed over back and forth between two BSs. This effect is common in a HHO. With a SHO, there is no hysteresis margin, resulting in less delay. This is accomplished by “instantaneous” switching to the best BS signal during a SHO with handoff hysteresis [28].

However, a SHO may reduce the system performance capacity-wise. During a SHO, the second BS transmits to a given MS the same signal as the first BS does. The transmitted power, therefore, becomes unavailable for allocation to other MSs of that second BS.

However, under the best circumstances, where propagation losses from each BS to the MS are the same and the power levels received from the two BSs are nearly equal, each BS would need to transmit less power than before. This could be ideally 3 dB less for each transmitter if it receives exactly equal unfaded signals and combines them coherently, so that the total interference or power allocation requirements are unchanged. Thus, signals destined for MSs in SHO will be provided the same total energy. It would simply be redistributed equally to the two BSs transmitting to each such MS [8].

In addition, FL interference (to other MSs) increases when a SHO is in progress, since several BSs are transmitting what would be otherwise transmitted by a BS. For example, a MS in a 2-way SHO may contribute approximately twice as much interference as MSs that are not in SHO [8]. Nonetheless, SHO implementation is more complicated compared to HHO implementation. A typical SHO process is shown in Figure 4.

Figure 4: A Typical Soft Handoff (SHO) Process

Figure 4(a) shows that a MS is currently within the coverage area of the BS_A , and the Active Set has only 1 entry, i.e., BS_A . As the MS moves, the received Pilot signal strength of the BS_B becomes stronger and eventually exceeds T_{ADD} . The BS_B will be added to the Active Set and a DCCH/FCH is allocated by the BS_B as shown in Figure 4(b). Now, the MS receives transmission from both the BS_A and BS_B . As the MS continues to move further, the received Pilot signal strength of the BS_A begin to deteriorate and drop below T_{DROP} . The BS_A is removed from the Active Set and added to that Candidate Set after the Handoff drop timer expires. The DCCH/FCH between the MS and BS_A will be disconnected and other communication links are unaffected as shown in Figure 4(c) and (d). Note that SCH is not shown in the figures.

4.4 Call Dropping

Call dropping is the process where an active MS is forced to drop its entire communication links with its serving BSs. When a MS begins to experience outage (its received E_b/I_o samples of SCH and/or joint E_b/I_o samples of DCCH/FCH falls below 4.5dB), the MS will begin to request more power allocation via a CLPC. The increase in the allocated power also increases co-channel interference to other MSs in the system. This increase in interference level further degrades the channel quality of all other MSs, causing even more request for increase in power allocation (via CLPC). This snowball effect is detrimental to the overall system performance. Therefore, the system would have to remove some of these MSs from the system once the communication links of these MSs can no longer be sustained and begin to cause unnecessary interference to

other MSs in the system. When all communication links of a MS are dropped, all SCH and/or DCCHs/FCHs allocated to this MS will be relinquished to their respective owners.

Call dropping is necessary as it may free up some much-needed resources and provide some relieve to the heavily loaded system. All other MSs may be benefited from the reallocation of the relinquished power resources.

An active MS is forced to drop all its communication links if one of the two following conditions is met:

1. The average of 8 consecutive E_b/I_o samples of DCCH, FCH or SCH falls below 3dB,
2. The MS fails a SCH HHO attempt.

Once a MS is admitted into the system, the received E_b/I_o of SCH and DCCH/FCHs are monitored throughout the duration of the call. When a MS experiences an outage, it attempts to request more FL power via the CLPC. If the serving BS doesn't have the power resources to do so, the received E_b/I_o may remain below 4.5dB [19][24]. Once the average of 8 consecutive samples fall below 3dB, this MS will be dropped.

As described in detail in section 4.3.1, if a HHO attempt fails due to low received E_c/I_o of the serving BS and lack of power resource at the target BS, the MS will be dropped.

4.5 Power Control

On the FL, all BSs use the same carrier frequency. Each communication link between a BS and a particular MS would also reach all other MSs in the form of co-channel interference. However, the greater the distance between the MS and interference

transmitter or BS, the weaker the interference becomes due to the propagation loss. In order to ensure good quality of service throughout the cell, the received signal in the borderline area of the cell must be strong. Hence a FL power control is applied to keep the co-channel interference low and the capacity of the system and the QoS high [27].

In a DS-CDMA system, power control is a vital necessity for the system operation. The capacity of a DS-CDMA cellular system is interference limited since the channels are neither separated in frequency nor in time, and the co-channel interference is inherently strong. A single MS exceeding the limit on FL transmitted power could affect the link quality of all other MSs. The power control systems have to compensate not only for signal strength variations due to the varying distance between the BS and the MS, but must also attempt to compensate for signal strength fluctuations of the wireless channel. These fluctuations are due to the changing propagation environment (due to shadowing, for example) between a BS and a MS as the MS moves across the cell [27].

The effective use of power control in DS-CDMA cellular systems reduces the co-channel interference and thus improves the quality of communication links of the MSs. It also enables the frequency to be reused in every cell, which in turns enables features such as soft handoff and base station diversity. All together, these help enhance the capacity of the system [27].

In this study, a Closed Loop Power Control (CLPC) by messaging is implemented. Specifically, the CLPC is performed in every simulation update cycle, i.e., twice per second. Without physical layer modeling, the CLPC bases its decision on an actual communication link performance parameter, i.e., the received SINR or E_b / I_o . The

CLPC is performed on all traffic channels, i.e., SCH, DCCH and FCH, separately. Every MS measures the E_b / I_o for each channel and calculates how much more or less power is needed to achieve the target E_b / I_o . The MS then reports back to the serving BS about the power adjustment in dB by messaging on the assumed error-free RL via FCH or DCCH every 0.5 seconds.

The MS may be required to increase or decrease the power allocation on the FL transmitted power. Due to the slow update period, the power control step size is not limited to 0.5 dB or 1dB. The MS can have its power allocation adjusted by as much as needed in order to meet its target E_b / I_o . Hence, a MS generally may need only one power control cycle to achieve its target E_b / I_o . If the MS requires having its power allocation reduced, the BS will do so accordingly. If the MS requires having its power allocation increased, the BS will try to allocate as much power as required provided subject to availability. If the remaining power resource of a BS is smaller than the amount of extra power required by a MS, the remaining power will be allocated. At this point, the BS is operating at full capacity and all other power increment requests hereafter will be ignored and all new or active call admission requests will be rejected.

When MSs don't get the power they need, they may fail to meet their target E_b / I_o in the immediate or subsequent simulation update cycles. Those MS will attempt to request power increment in the next CLPC cycle, though their requests may not be successful. In the meantime, the Call Dropping process monitors the target E_b / I_o and may have to force the MS to have their communication links dropped if the MS cannot recover from the outage.

5 Simulation Strategy

This chapter describes the details of the simulation strategy used in this study to estimate the system capacity of mixed traffic services. Which estimator was used and how it was used, and how to determine when a simulation is running at steady state is explained. As well, the computation of serial correlation and the construction of confidence interval for the approximate value of the steady state average are fully described.

Since the objective of this simulation study is to evaluate the long-term system capacity and to observe the resulting effects of supporting mixed traffic services, the steady state behavior of the simulator is studied. Hence, the first requirement is to establish when the simulation is running at steady state for any combinations of traffic loads. The traffic loads of the combined traffic services are adjusted so that the approximate long-term average of the estimator gets closer to the desired value. The whole simulation is repeated for some different combinations of mixed traffic loads.

In every simulation, the traffic loads of these two traffic services are chosen so that the system service coverage is 95%. In other words, the system has a 5% probability of blocking. In this study, the Voice traffic load is fixed and an initial Data traffic load is chosen. A steady state simulation is performed to obtain the probability of blocking for this combination of mixed traffic loads. If the probability of blocking is higher or lower than a desired value, the Data traffic load is lowered or increased, respectively, with the assumption that the new traffic loads combinations will produce a probability of blocking that is closer to the desired value.

The initial condition of the system is not important and the steady state parameters of the system should be independent of the initial conditions. Due to the stochastic nature of the simulation, the results generated by a single simulation run of somewhat arbitrary length without any confidence measure is not reliable[20].

5.1 Steady State Simulation

In this study, a warm-up period of at least 60-minutes is used. However, after 60 minutes of simulation time, the simulation is not yet considered running at steady state, but it is assumed that all obvious initialization biased elements have been eliminated.

Nonetheless, another method is needed to determine if the simulation is running at steady state with some measure of confidence.

The main strategy is to determine the steady state average of blocking probability before the approximate value of the Data traffic load can be measured. Study in [21] proposed that constructing a confidence interval for the steady state average of the point estimator is an approach to assess the accuracy of the average of the point estimator. There are two basic approaches to construct a $100(1-\alpha)\%$ confidence interval for the steady state average of the point estimator:

1. **Fixed Length Simulation:** construct a confidence interval from an arbitrary fixed sample size, or
2. **Variable Length Simulation:** increase the sample size sequentially until an "acceptable" confidence interval can be constructed.

5.1.1 Fixed Length Simulation

A fixed length simulation may produce a point estimator with a big variance, and it may differ greatly from the corresponding true measure. The net effect is that there may be a significant probability of making erroneous inferences about the systems under study. If the total sample size is made sufficiently large, then the actual coverage realized by one simulation run would be closer to the desired level; however, what is sufficiently large for one stochastic system may not be adequate for another. Thus, in practice, a simulator will not know the actual coverage of its confidence interval [21]. A procedure is needed to determine the total sample size necessary to achieve an acceptable coverage during a simulation run.

5.1.2 Variable Length Simulation

The method to construct a $100(1-\alpha)\%$ confidence interval for the steady state average of the point estimator is considered here. The method begins with a minimal run length and sequentially increases this run length (collect more observations or samples) during the course of the simulation until a set of conditions is satisfied [20][21]. This method is called a batch-mean method and it requires only a single simulation run.

In addition to this problem of coverage, a simulator might want to determine a run length large enough to produce a confidence interval having half-length sufficiently small compared to the approximate steady state average of the point estimator to allow for the drawing of useful conclusions [20].

5.1.3 Sampling of Blocking Probability

The simulation time is divided into 0.5 seconds interval. On every 0.5-seconds interval, the number of new call admission requests and the number of admission requests rejected are tallied. A sample is defined as the blocking probability within the 0.5 seconds interval provided that the number of new call admission requests is greater than zero,

$$\chi = \Pr \left(\frac{\# \text{requests blocked}}{\# \text{requests} > 0} \right).$$

In other words, no sample is collected if the number of request is zero during the time interval. This value χ is considered as a sample of steady state probability of blocking. After a certain number of samples are collected, the batch mean method is then used to determine if:

1. The number of samples is sufficiently large enough to generate a low serial correlation (see section 5.3), and
2. A steady state average value of the point estimator with a tight confidence interval can be constructed (see section 5.4).

If both criteria are met, it would be concluded that the simulation is running at steady state. The approximate steady state average value of the point estimator will then be compared against a pre-determined value. The simulation will be stopped or continued depending on the value of the approximate steady state average value of the point estimator.

5.2 Batch Mean Method

The batch-mean method [21] attempts to reduce the serial correlation by batching the collected samples. Thus, the method monitors the apparent serial correlation (see section 5.3) and calls for a larger batch size and hence further sampling if the apparent serial correlation is too large. Standard estimates of serial correlation are seriously biased when based upon a small number of samples. The method partitions the collected samples into a large number of small batches when estimating serial correlation. If this estimated serial correlation is either:

1. The estimated serial correlation of 400 batches is negative, or
2. Positive, but moderately small, and halving the number of batches does not increase estimated serial correlation,

Then, it is assumed that the true serial correlation among small number of large batches is negligible and a $100(1-\alpha)\%$ confidence interval can be constructed. If the half-length of the interval is sufficiently small compared to the approximate steady state average of the point estimator (see section 5.4), the procedure accepts it and stops; otherwise, it collects more samples and return to step (2).

The implementation is summarized in the following:

1. Set $i \leftarrow 1, n_0 \leftarrow 600, n_1 \leftarrow 800$. Collect n_1 samples;
2. Partition the n_1 samples into 400 batches, each of size $n_1 / 400$. Estimate the serial correlation for 400 batches and denote the serial correlation as SC_1 . If $SC_1 \geq 0.4$, go to (5). If $SC_1 < 0$, go to (4), otherwise go to (3).

3. Partition the n_1 samples into 200 batches, each of size $n_1/200$. Estimate serial correlation for these 200 batches and denote the serial correlation as SC_2 . If $SC_2 > SC_1$, go to (5); otherwise go to (4).
4. Partition the n_1 samples into 40 batches, each of size $n_1/40$. Construct a nominal 90% confidence interval assuming that the 40 batches are independent and ignoring that the batches were constructed sequentially (see section 5.4). If the interval is acceptably small relative to the current approximate value of steady state average (ratio of interval half-width to approximate steady state average of the estimator is smaller than 0.2), stop. Otherwise go to (5).
5. Set $n_2 \leftarrow 2 \cdot n_0$. Collect $n_2 - n_1$ additional samples.
6. Set $n_0 \leftarrow n_1$, $n_1 \leftarrow n_2$ and go to (2).

5.3 Serial Correlation Computation

Here, we have a sequence of possibly correlated samples, $X_1, X_2, X_3, \dots, X_n$. The serial correlation of the samples can be estimated in the following [22],

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i, \quad (15)$$

$$\rho = \frac{\sum_{j=1}^{n-1} (X_j - \bar{X})(X_{j+1} - \bar{X})}{\sum_{j=1}^n (X_j - \bar{X})^2}, \quad (16)$$

$$k = n/2, \quad (17)$$

$$\bar{X}_1 = \frac{1}{k} \sum_{j=1}^k X_j, \quad (18)$$

$$\rho_1 = \frac{\sum_{j=1}^{k-1} (X_j - \bar{X}_1)(X_{j+1} - \bar{X}_1)}{\sum_{j=1}^k (X_j - \bar{X}_1)^2}, \quad (19)$$

$$\bar{X}_2 = \frac{1}{k} \sum_{j=k+1}^n X_j, \quad (20)$$

$$\rho_2 = \frac{\sum_{j=k+1}^{n-1} (X_j - \bar{X}_2)(X_{j+1} - \bar{X}_2)}{\sum_{j=k+1}^n (X_j - \bar{X}_2)^2}, \quad (21)$$

and the jackknifed estimate of serial correlation is

$$\hat{\rho} = 2\rho - \frac{(\rho_1 + \rho_2)}{2}. \quad (22)$$

5.4 Confidence Interval Computation

Let $Y_1, Y_2, \dots, Y_{40}$ be the 40 batch means assuming that these 40 batches are independent and ignoring the fact that they were constructed sequentially. Let β be the point estimator of the steady state probability of blocking and m be the number of batch means. Hence, the sample mean $\hat{\beta}$ based on the batch means [23] is defined by

$$\hat{\beta} = \frac{1}{m} \sum_{i=1}^m Y_i . \quad (23)$$

The sample variance, S^2 , of $\hat{\beta}$ can be computed by

$$S^2 = \sum_{i=1}^m \frac{(Y_i - \hat{\beta})^2}{m-1} . \quad (24)$$

When the Y_i are i.i.d., the sample variance, S^2 , is unbiased estimator of the population variance $\sigma^2 = \text{var}(Y_i)$. Since the variance of $\hat{\beta}$ is given by

$$\sigma^2(\hat{\beta}) = \frac{\sigma^2}{m} , \quad (25)$$

an unbiased estimator of $\sigma^2(\hat{\beta})$, with $f = m-1 = 39$ degrees of freedom, is provided by

$$\hat{\sigma}^2(\hat{\beta}) = \frac{S^2}{m} \quad (26)$$

or

$$\hat{\sigma}(\hat{\beta}) = \frac{S}{\sqrt{m}} . \quad (27)$$

Hence, an approximate 100(1- α)% confidence interval for β is given by

$$\hat{\beta} - t_{\alpha/2, 39} \hat{\sigma}(\hat{\beta}) \leq \beta \leq \hat{\beta} + t_{\alpha/2, 39} \hat{\sigma}(\hat{\beta}) \quad (28)$$

where $t_{\alpha/2, 39}$ is the 100(1- α) percent point of a t -distribution with 39 degrees of freedom.

Eq. (28) is valid provided that the point estimator, $\hat{\beta}$, is unbiased. Eq. (27) is sometimes denoted as $s.e.(\hat{\beta})$, and it is called standard error of the point estimator $\hat{\beta}$.

The standard error is a measure of precision of a point estimator [23].

Thus, a 90% confidence interval of the steady state average of probability of blocking can be computed by,

$$\hat{\beta} - \Delta \leq \beta \leq \hat{\beta} + \Delta \quad (29)$$

where
$$\Delta = 1.684 \frac{S}{\sqrt{40}} . \quad (30)$$

The goal of each simulation is to produce a 90% confidence interval for which the ratio of the confidence interval half width (Δ) to the approximate steady state average of the point estimator ($\hat{\beta}$), is less than a specified tolerance, γ . In our study, γ is set to 0.2.

Thus, a simulation is considered running at steady state if

$$\frac{\Delta}{\hat{\beta}} < \gamma = 0.2 \quad (31)$$

After the serial correlation of the samples is established to be acceptably low, the approximate steady state average of the point estimator is calculated and a 90% confidence interval is constructed. If the 90% confidence interval is said to be sufficiently tight (Inequality (31)), the simulation is concluded to be running at steady state.

5.5 Data Traffic Load Adjustment

In this simulation study, a simple back propagation method is used to adjust the Data traffic load so that the steady state average of the blocking probability will eventually approximate the desired output. For each combination of mixed traffic services, the Voice traffic load is fixed. For each value of fixed Voice traffic load, the Data traffic load is adjusted to produce a 5% probability of blocking with a tight 90% confidence interval.

If the steady state average blocking probability is smaller than 4.9%, the Data traffic is increased. Similarly, if the blocking probability is larger than 5.1%, the Data traffic is decreased. When adjustment is needed, all samples are discarded and the whole simulation is repeated. If the approximate steady state average of the probability of blocking falls between 4.9% and 5.1%, the simulation stops and other statistics are collected. The Voice traffic load is then set to a different value and the whole simulation is repeated.

When we study Voice-only system capacity, the Data traffic load is set to zero. An initial value of Voice traffic load is set and a simulation is performed. When the approximate steady state average value of the probability of blocking doesn't fall between 4.9%-5.1%, the Voice traffic load is adjusted and the simulation is repeated.

The summary of the whole simulation strategy is depicted in Figure 5, on page 61.

Figure 5: Summary of Simulation Strategy

6 Simulation Cases and Measurements

This chapter explains how the simulation cases are selected, and how the initial values of Voice and Data traffic loads are chosen before any simulation is performed.

Ideally, the simulator is capable of obtaining the traffic loads of Voice and Data services regardless of what initial values of the traffic loads are set to. However, the simulator may take weeks or even months in order to find a Data traffic load that couples with a fixed value of Voice traffic load that gives a 5% blocking probability. Although the final results of a steady state simulation is not influenced by the initial values, these initial values should be chosen very carefully hoping that these initial values will drive the simulation to achieve their desired results quickly.

6.1 Initial Values Selections

Based on the simulation strategy described in Chapter 5, initial values of Voice and Data traffic loads will be set before any simulation is performed. Once the simulation is running at steady state, the average system blocking probability is generated and compared with a predetermined value of 5%. If the blocking probability falls within a desired range, only the value of the Data traffic load is adjusted and the simulation is continued. Ideally, the simulator is capable to determine the Data traffic load with a fixed Voice traffic load using any arbitrary initial value of the Data traffic load.

However, the simulator may take tens of hours before a steady state is reached. If the initial value is too far off from the true value, the simulator may take days if not weeks

before desired results are obtained. Therefore, initial values of Data traffic loads should be chosen in such a way that they are chosen as close to the true values as possible.

6.2 Single Service System Capacity

Before any mixed traffic simulation is performed, it was decided to get the Erlang capacities of Voice only homogeneous systems. In this case, the Data traffic load is set to zero. The initial value of Voice traffic load with the FL orthogonality factor of zero is chosen based on the work done in [19]. Once the simulation is running at steady state, the steady state average system blocking probability is compared with a predetermined value of 5%. If the blocking probability falls within 4.9% and 5.1%, the simulation is stopped. Otherwise, the initial value of Voice traffic load is increased by 0.1 Erlangs or reduced by 0.1 Erlangs if the resulting blocking probability is smaller than 4.9% or greater than 5.1%, respectively. All previously collected data is discarded and the simulation is continued using the newly adjusted value of Voice traffic load.

Generally, the Erlang capacity of a system with a higher FL orthogonality factor has a lower FL Erlang capacity [4][5][15]. Hence, once the Erlang capacity of a Voice only system with a FL orthogonality factor of zero is found, the resulting Voice traffic load will be used as the initial value for a system that has a next higher FL orthogonality factor, and so on.

6.3 Mixed Service System Capacity

After the Erlang capacities of Voice only systems with different FL orthogonality factors are obtained, simulations of mixed traffic can begin.

Based on the observations described in [4][12][15], the number of Data MSs is almost equal to the number of Voice MSs based on the ratio of their data rates, activity factors and SINRs. Since the ratio of their data rates and activity factors is 38.75 ³(SINRs are equal in both traffic services), it is assumed that one Data MS is equivalent to 38.75 Voice MSs. This assumption is made only for the purpose of selecting the initial values of Voice and Data traffic loads. Therefore, the first initial value of mixed traffic loads is set under the assumption that one unit Erlang drops in Voice traffic load is coupled with 1/38.75 units Erlang increase in Data traffic load.

Once a set of initial values of Voice and Data traffic loads are selected, simulation is executed. When the simulation is running at steady state, the steady state average blocking probability is compared with a predetermined value of 5%. The simulation will stop if the resulting average blocking probability is within the desired range of 4.9 - 5.1%. Otherwise, the Data traffic load will be adjusted according the difference of the resulting blocking probability and the desired blocking probability. If the difference is big, the Data traffic loads will be reduced or increased more aggressively. In the simulator, the Data traffic load is adjusted according to the following range:

1. If blocking probability > 10%, the current Data traffic load is reduced by 0.5 Erlangs;
2. If blocking probability is between 0 – 4% or 6 – 10%, the current Data traffic load is reduced by 0.1 Erlangs;

³ Data: 144 kbps SCH + 4.8 kbps DCCH, 100% activity factor in both channels

Voice: 9.6 kbps FCH, 40% activity factor

3. If blocking probability is between 4 – 6%, but not within the desired range, the current Data traffic load is reduced by 0.02 Erlangs.

After the Data traffic load is adjusted, the simulation is continued. All data collected using the previous Data traffic load will be discarded and a new set of data will be collected.

Once the first Erlang capacity of a mixed traffic system is obtained, extrapolation is used to find the next initial value of the Data traffic load that couples with a fixed Voice traffic load.

6.4 System Capacity of Different Values of FL Orthogonality Factors

In order to investigate the effect of the FL orthogonality factor on the system capacities, 4 sets of simulations were carried out using 4 different values of FL orthogonality factors.

In each set of simulations, all MSs in the system will receive a certain degree of same cell interference from their serving BS (for both single service and mixed traffic simulations).

Table 2: 4 Simulation Cases

Simulation Sets	FL Orthogonality Factor
Case 1	0.0 (Perfect Orthogonality)
Case 2	0.2
Case 3	0.8
Case 4	1.0

A FL orthogonality factor of zero averages the FL channels are perfectly orthogonal where a MS receives no same cell interference. The FL orthogonality factor is represented as ζ_i .

By setting the FL orthogonality factors to zero or one, an attempt was made to observe the effect of extreme cases of FL channel orthogonality on the system capacity and performance. In addition, two additional sets of simulations are selected, i.e., orthogonality factors of 0.2 and 0.8. The goal was to see if the resulting effect of the change in the orthogonality factor from 0.0 to 0.2 is the same as the resulting effect of the change in the factor from 0.8 to 1.

6.5 Results Collected

In addition to the Voice and Data Erlang capacities, the following results will also be observed and collected during the simulations:

1. Initial power required by Voice and Data MSs,
2. Total FL Transmitted Power by the cell of interest, i.e., center cell.

Whenever a MS requests for an admission, the estimated initial power required by this MS will be recorded, whereas the total transmitted FL power will be recorded for every simulation update period, i.e., 0.5 seconds. The initial power coupled with the total FL transmitted power will provide us with some insights on the impacts of different degree of FL channel orthogonality on the capacity as well as the relationships between Voice and Data services.

7 Results and Discussion

This chapter describes the results obtained from the simulations. All results were collected after the simulations were running at steady state and the system blocking probabilities were within the desired range of 4.9% - 5.1%.

Observations regarding the interaction between two inherently different traffic services are described in this chapter. The effects of different traffic service on the system capacity as well as some performance-related issues such as initial power required and FL transmitted power will also be discussed.

7.1 Erlang Capacity of Single Service Systems

Simulations of Voice only systems for 4 different values of FL orthogonality factors were performed and the Erlang capacities of these systems are listed in the following:

Table 3: Erlang Capacity of Voice-Only Systems

FL Channel Orthogonality Factor	1.0	0.8	0.2	0.0
Voice Traffic Load in Erlangs	19	20	21.3	23

By referring to Table 3, it is expected that the Erlang capacity of Voice-only system drops as the FL channel orthogonality diminishes. Although the amount of FL orthogonality factors changed by 0.2, the difference in term of capacity changes quite significantly. When the factor changes from 0.0 to 0.2, the Voice capacity drops by 1.7 Erlangs, while the capacity drops only by 1.0 Erlang when the factor changes from 0.8 to 1.0.

Due to the desired blocking probability, SINR requirement, data rate of Data MSs and simulation update cycle duration, the capacities of the Data-only systems cannot be obtained. In other words, the system cannot support a Data-only system at a blocking probability of 5% under the current level of radio resources.

7.2 Erlang Capacity of Mixed Service Systems

The Voice and Data Erlang capacities of 4 sets of systems with different FL orthogonality factors (0.0, 0.2, 0.8 and 1.0) are plotted in Figure 6, on page 69.

The y-axis shows the Data traffic loads, while x-axis depicts the Voice traffic loads. The curves show different combinations of traffic loads that can be supported by the system at a fixed blocking probability of 5%. The x-axis intercepting points are the traffic loads of Voice.

If a Data MS is viewed as a multiple of Voice MSs determined simply by the ratio of their bit rates, activity factors and SINR, a multiple units of Erlang increase in Voice traffic loads should be coupled with one unit of Erlang drop in Data traffic load as described in [4][12][15]. In this study's system, the ratio of their bit rates and activity factors is 38.75 (SINRs are equal in both traffic services) where the combined data rates and activity factors of Data and Voice MSs are 148.8 kbps (144 kbps of SCH + 4.8 kbps of DCCH, both at an activity factor of 100%) and 3.84 kbps (9.6 kbps of FCH at an activity factor of 40%), respectively. However, by examining the capacity curves, the Data traffic load drops more rapidly than the ratio when the Voice traffic load increases, for all values of the FL orthogonality factors. For example, if one looks at the capacity curve of the system with a perfect FL channel orthogonality, the data traffic load drops by

0.9 units Erlangs when the Voice traffic load increases from 5 to 20 Erlangs (points that are labeled “A” and “B”), as shown in Figure 6.

Figure 6: FL Voice and Data Erlang Capacity for Different Orthogonality Factors.

The number of Voice MSs in the system grows as the Voice traffic load increases. The number of Voice MSs that has a 2-way or 3-way SHO also grows. Accordingly, the co-channel interference caused by these Voice MSs in SHO grows. This causes all new and active MSs (Voice and Data) to require more power allocation through power control to counter the impact of the increase in the received interference. Power resource of a BS is deprived and room for admitting new MSs is getting smaller. Since Data MSs require higher power allocation to compensate for their low processing gains, they are more likely to suffer a higher blocking probability. However, the Data traffic load supported

by mixed traffic system drops more rapidly than the ratio of 1/38.75. The reason will become clear when one looks at the total FL transmitted power and initial power required by both the Voice and Data MSs.

When the FL orthogonality factor changes, the resulting effects are quite consistent with the observations made in Voice only systems. When the FL orthogonality factor changes from 0.0 to 0.2, the capacity of mixed traffic system drops significantly. Also the drop is greater than the drop in capacity when the factor changes from 0.8 to 1.0. This observation is quite similar to the observations made in the Voice only systems. The probable cause will also become clear when one looks at the total FL transmitted power and initial power required by both the Voice and Data MSs.

7.3 Total FL Transmitted Power

The evaluations on the Erlang capacity of Voice and Data traffic services and the impacts of FL orthogonality factors on the system performance cannot be complete without looking at the total FL transmitted and their estimated initial power required.

For every simulation update cycle, i.e., 0.5 seconds, the total FL transmitted power is sampled and recorded. The steady state averages total FL transmitted powers of each simulation are plotted in Figure 7, on page 71.

The y-axis shows the average total FL transmitted power. Each point on the curves represents an average total FL transmitted power of a mixed traffic system. The points that are labeled as "A" to "L" in Figure 7 and subsequent figures and correspond to the points that are labeled "A" to "L" in Figure 6, respectively. The x-axis is just a reference

to the Voice traffic loads of different mixed traffic systems. For example, point “A” in Figure 7 depicts the average total FL transmitted power of the mixed traffic system with a perfect FL channel orthogonality where Voice and Data traffic loads are 5 and 1.9 Erlangs (point “A” in Figure 6), respectively. While point “E” in Figure 7 depicts the average total FL transmitted power of the mixed traffic system with a FL orthogonality factor of 0.2 where Voice and Data traffic loads are 20 and 0.4 Erlangs (point “E” in Figure 6), respectively.

Figure 7: Average Total FL Transmitted Power

Figure 7 shows that the average total FL transmitted powers grow steadily as the Voice traffic load increases. The increasing number of Voice MSs in 2-way or 3-way SHO causes the power resources to be deprived further, which in turn increases the average

total FL transmitted power. For example, when the Voice traffic load changes from 5 Erlangs (point “A”) to 20 Erlangs (point “B”) for the system with FL orthogonality factor of zero, the average total transmitted power grows from about 31.5 dBm to 33.5 dBm.

Although the difference in average total FL transmitted power between systems with FL orthogonality factors of 0.0 and 1.0 is less than 1 dB, the change in the average total FL transmitted power when the orthogonality factor changes from 0.0 to 0.2 is greater than the change in the transmitted power when the factor changes from 0.8 to 1.

7.4 Estimated Initial Power Required

The average estimated initial power required by either a Voice MS or a Data MS are collected when a MS (Voice or Data) sends an admission request to the target BS.

Figure 8, on page 73, and Figure 9, on page 74, show the average estimated initial power required by Voice MSs and Data MSs, respectively. For comparison, the differences in the average initial power required by Voice and Data MSs are plotted in Figure 10, on page 75.

By comparing both the average estimated initial power curves to the average total FL transmitted power curves, it appears that the estimated initial powers required by both Voice and Data MSs are correlated to the average total FL transmitted power. The average estimated initial power required is greater when the average total FL transmitted power gets higher (higher received co-channel interference from neighboring BSs).

When the Voice traffic load increases, the average of total FL transmitted power grows and causes a higher interference to all MSs in the system. Since the total FL transmitted

power is higher, all new Voice and Data MSs require a higher initial power in order to support their respective initial SINR. For example, a Voice MS in a system with perfect FL channel orthogonality is expected to require at least 1 dB more power when the Voice traffic load increases from 5 to 22 Erlangs.

Figure 8: Average Initial Power Required by Voice MSs

For Voice MSs, the difference in average initial power required is about 5 dB when the FL orthogonality factor changes from 0.0 to 1.0, while the difference is about 8 dB for Data MSs. This shows that the impact of the same-cell interference due to imperfect FL channel orthogonality is more potent to a Data MS than to a Voice MS. In other words, Data MSs are more likely to experience a higher blocking probability due to the increase

in same-cell co-channel interference. Thus, this shows that the FL orthogonality factors also play a quite important role in the call admission controls of different types of MSs.

Figure 9: Average Initial Power Required by Data MSs

By referring to Figure 8 and Figure 9, the difference in initial power required by a Voice or a Data MS when the orthogonality factor changes from 0 to 0.2 is greater than the difference in initial power required when the factor changes from 0.8 to 1. For instance, a Data MS is expected to require about 3 dB more initial power when the orthogonality factor changes from 0 to 0.2, while the same MS is expected to require only less than 1 dB more initial power when the factor changes from 0.8 to 1.

This observation is consistent with the trends of the drops in Erlang capacity as well as the increase in total FL transmitted power that was described previously. The probable cause of this phenomenon is due to the diminished effect of the FL orthogonality factor. The incremental effect of the FL orthogonality factor diminishes when the value of the factor increases.

Figure 10: Difference of Initial Power Required by Voice and Data MSs

Based on the ratio of their data rates and the initial power formulations described in Eqs. (12), (13) and (14)⁴, a Data MS would require an approximately 12 dB more initial power

⁴ Voice activity factor is not considered in these equations.

than a Voice MS under the same channel conditions and the same degree of FL orthogonality factor. The curves in Figure 10 show that the difference in initial power required by a Data MS and a Voice MS doesn't change significantly as the Voice traffic load increases. The difference is around 11 to 12 dB when the orthogonality factor has a value of 0.2, 0.8 or 1. However, the difference is the greatest when the orthogonality factor has a value of zero and the difference is around 9 to 10 dB. In other words, a MS (Voice or Data) in a system having an orthogonality factor of zero may require up to 3 dB less initial power than the same MS in a system having an orthogonality factor of 1.

Figure 8, Figure 9 and Figure 10 show that the Voice and Data MSs suffer a different degree of interference when the capacity load and/or the FL channel orthogonality factor change. For these reasons, a high-rate Data MS cannot, and should not, be assumed as equivalent to a multiple of low-rate Voice MSs that is determined simply by the ratio of their bit rates, activity factors and SINR requirements, which has been suggested by [4] [12][15].

8 Conclusions

This chapter summarizes the work presented in this study, which focused on the system capacities and provided an alternative way to estimate FL capacity of a wide-band mixed traffic DS-CDMA cellular system using simulations, instead of a traditional way of numerical analysis.

First, Chapter 2 explained the fundamentals regarding the spread spectrum technology followed by the reasons why the system capacities were estimated using simulations instead of numerical analysis. Also, in this chapter, other methods of estimating the capacities of similar systems were reviewed. The fairly complex interactions, inherent properties of different traffic service types make the traditional way of numerical analysis extremely difficult.

A description of how the DS-CDMA cellular system is modeled is given in Chapter 3. As well, simulation plane, different channels and their respective properties were described in this chapter. Chapter 4 then discussed some of the important call procedures such as Admission Control, Handoff Control, Power Control, etc. Chapter 5 described how to determine and perform steady state simulations. This study has presented an effective simulation strategy to estimate the steady state capacity of a DS-CDMA system.

In Chapter 6, how simulation cases and the initial values are selected were explained. In Chapter 7, the simulation results obtained were discussed in detail. The effects that different types of MSs have on the system performance such as capacity, total transmitted

power and estimated initial power required by Voice and Data were also discussed in this chapter.

Overall, this study has achieved the following 3 primary objectives:

1. The Erlang capacity of an Integrated Voice and Data DS-CDMA cellular system through simulations has successfully been estimated. By using the simulator, the system capacity of different combinations of mixed traffic loads is generated.
2. As well, the effects that imperfect FL channel orthogonality has on the system capacity have been shown. For instance, the system capacity of the cellular system drops and high-power Data MSs becomes more vulnerable as the FL channel orthogonality diminishes. Intuitively, imperfect FL channel orthogonality plays quite an important role affecting the received same-cell co-channel interference at every MS. It causes all new MSs to acquire higher initial power allocation during the admission process. It always causes all active MSs to require higher power allocation so that their SINR can be maintained. Also it has been shown that the FL channel orthogonality affects Voice and Data MSs differently. The diminishing FL channel orthogonality, coupled with the increase in Voice traffic loads make the Data traffic loads to drop more rapidly, far greater than the ratios based on their bit rates, activity factors and SINR requirements.
3. The interactions between two inherently different traffic services and their impacts on the system capacities have also been captured. The following additional observations were also made. A Data MS cannot, and should not, be viewed as a multiple of Voice MSs determined simply by the ratio of their data rates, activity factors and SINR requirement.

In addition to the above-noted observations, the average total FL transmitted power coupled with the average initial power required by Voice and Data MSs can certainly be used to design and improve some of the call processing algorithms such as Power

Control, Admission Control, Handoff (Soft and Hard) Control, etc. The steady state simulation strategy is surely producing more reliable long-term results.

In summary, this study shows that the steady state simulator is definitely an effective tool to evaluate other performance issues of a DS-CDMA system. The simulator can also be enhanced to simulate packet switched data service. More recommendations for future study will be suggested in the next chapter.

9 Future Work

To extend the achievements of this study and step forward in this area, the following work could be done in the future in the following order of priority:

1. The optimization of the simulator to run more efficiently so that the simulation update cycle duration can be reduced and produce more accurate results;
2. The implementation of new traffic models for other data service applications, such as multi-rate Packet Switching Data service;
3. The enhancement of the admission control to integrate and utilize the Voice, Circuit Switched and Packet Switched Data services within the same system;
4. The modification of the simulator to estimate the Reverse Link (RL) capacity and then the capacity of a complete (FL and RL) system.

Last but not least, the steady state simulator can also be used to evaluate any improved call processing algorithms such as power control, handoff control, etc.

Parameters Used in Simulations

Name (description)	Value
Simulation update period (Power Control, Pilot Set update, etc.)	0.5s
Simulation warm-up period	>3600s or >1 hr
Cell Radius	3.85 km
Average Holding Time of a Call (used in Poisson Process)	120s
Noise Floor	-118 dBm
Shadow (lognormal , mean)	0 dB
Shadow (lognormal, standard deviation)	6 dB
Correlation (shadowing)	Enable
CDMA Propagation Loss Model	Hata simplified
Target Eb/Io (for all FCH/DCCH/SCH)	5.5dB
Call setup Ec/Io (pilot) threshold	-7dB
Eb/Io F-FCH/DCCH/SCH Drop Call Threshold	3dB
Add Threshold (T_{ADD}) for Soft Handoff	-12dB
Drop Threshold (T_{DROP}) for Soft Handoff	-15dB
Bandwidth	3.6864MHz
FCH Data Rate	9.6kbps
DCCH Date Rate	4.8kbps
SCH Date Rate	144kbps
Maximum number of member in Active Set (SHO active)	3
Maximum number of member in Candidate Set	7
Forward Voice Activity Factor	0.40
Sync Channel Power	10.1 dBm
Pilot Channel Power	28.55 dBm
Paging Channel Power	16.1 dBm
Maximum FL Transmit Power	35.54 dBm

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