SOFT DROPPING POWER CONTROL

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ABSTRACT OF THE THESIS

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This work considers a power control algorithm for cellular communications systems in which a user's link quality objective, as measured by signal to interference ratio (SIR), varies with its transmitter power. In particular, as increased interference or reduced uplink gain leads a mobile to raise its transmitter power, that mobile lowers its SIR target. In this way, the likelihood of an infeasible power control problem in which users' transmitter powers rise to maximum is reduced. This graceful degradation of the SIR is termed soft dropping. Convergence proofs for a soft dropping power control algorithm are presented. Simulation results demonstrate performance improvements over fixed target SIR algorithms.

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Dedication

To my Father, Mother, Sister, friends and all my relatives.

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Chapter 1

Introduction

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact wih ships sailing the English Channel in 1897. New wireless communications methods and services have now been enthusiastically adopted by people throughout the world. The number of cellular telephone users in U.S. grew from a measly 25,000 users in 1984 to about 40 million in 1996, and since then wireless services have been experiencing customer growth rates well in excess of 50% every year. The sale of radio frequency bands has reaped sizable revenues for the FCC, as is evident in its latest round of bidding for "D", "E", and "F" broadband PCS (personal communication services) which raised more than $2.5 billion in total net revenue. This sale represents the Commission's final auction in the broadband PCS arena, barring possible re-auctions of any licenses. The narrowing pool of radio frequencies has built up pressure on the industry to provide for the exponential growth in the number of subscribers.

High speech quality, high capacity and low power consumption have been major goals of researchers and system providers throughout the evolution of cellular communications systems. Radio resource management techniques have played a pivotal role in the accomplishment of these objectives. Existing systems perform several distinct radio resource management tasks including admission control, channel assignment, power control, and handoff. Transmitter power control is central to the design of high capacity multiuser radio systems due to its interference controlling capability. It is desirable to optimize the system performance by efficient use of transmitter power. In this chapter we will introduce radio resource management (Section 1.2) in cellular systems and explain the interest in transmitter power control for multiuser radio networks in Section 1.4. In Section 1.5 we describe previous work on integrated radio resource management including power control. Section 1.6 presents the scope of the thesis.

1.1 Cellular Radio Networks

More than 15 years have passed since the first-generation mobile cellular communication services using analog frequency modulation (FM)/ frequency division multiple access (FDMA) started. Today, in addition to the analog systems, second generation macro- and micro-cellular digital systems have been introduced. Now wireless communication researchers are exploring for a highly reliable and high capacity digital system as the third or fourth generation of mobile cellular communications.

The mobile radio channel has always placed fundamental limitations on the performance of wireless communications systems. Unlike wired channels that are stationary and predictable, radio channels in cellular systems have transmission paths that can vary from simple line-of-sight to those that are severely obstructed by buildings, mountains, and foliage. Another challenge confronted by a mobile radio network is to maintain a connection and service quality independent of the mobility of the terminal. The speed of the motion influences the rate at which the signal level fades as a mobile terminal moves in space.

The radio frequency spectrum can be shared amongst the users in three basic ways giving rise to three fundamental multiple access techniques. In frequency division multiple access (FDMA), the frequency spectrum that is allotted for the wireless network is divided into a number of frequency bands. A user occupies one frequency band for the time it needs to transmit information. When the time of occupancy of a frequency band is divided into slots, the access technique is called time division multiple access (TDMA). A user would then occupy the frequency band only in the time slots that are assigned to it. The third type of multiple access is known as code division multiple access (CDMA) where a terminal is assigned a unique code consisting of a certain number of symbols called chips. When a terminal needs to communicate, it transmits on the carrier frequency common to all users but modulates its information with its unique code sequence before transmission. There are also schemes that are hybrid of the three basic multiple access schemes mentioned above. Simulations and analysis for the two broad categories of TDMA/FDMA and CDMA systems will be discussed in the following chapters.

1.2 Radio Resource Management

The establishment and maintenance of calls between base stations and mobiles requires several resource allocation techniques such as base station assignment, admission control, channel allocation (carrier frequency/time slot, etc.), transmitter power control (uplink/downlink), and handoff management. Due to the time and space varying nature of the system, radio resource management schemes have to adapt dynamically to the instantaneous interference and traffic situations. Indeed radio resource management becomes critical in the design of a cellular network that offers high capacity, high quality (as reflected in the achieved signal to interference ratio (SIR) or bit error rate (BER)), low blocking, and low dropping of calls. Key results have demonstrated that integrated radio resource management can help accomplish these objectives within specified quality constraints [17, 18, 20, 22].

The radio resource management algorithm consists of several subtasks, namely,

- *Base Station Assignment* – The assignment of an appropriate base to which the mobile can communicate.
- *Admission Control* – The selective denial of service to new calls arriving in the system in order to avoid the deterioration of link quality for ongoing calls.
- *Channel Allocation* – The allocation of an uplink (mobile to base station) and downlink (base station to mobile) pair of channels which provides for communication between the mobile and the base.

- *Transmitter Power Control* – The iterative control of uplink and downlink transmitter power of the mobile and the base respectively, to maintain link quality as the channel varies with time and control the interference level on those channels.
- *Handoff/Handover Management* – The switching of a user from its original base to a new base due to movement out of the old base's coverage area. The new base provides an improved connection.

1.3 General flow of sub-tasks in radio resource management

Radio resource management for a mobile is initiated when the mobile is trying to make a connection and ends when the connection is terminated. When a new call arrives in the service area, a base with the strongest beacon signal is allocated (*Base Station Assignment*). An admission check is then performed on the new mobile (*Admission Control*). If admitted, the base station allocates an uplink and downlink channel for communication (*Channel Allocation*). The conversation then begins with the specified uplink and downlink transmitter powers. The transmitter power is adjusted constantly depending on the strategy of power control (*Transmitter Power Control*). During the call, the link quality is repetitively checked and if certain handoff criteria are met, as specified by the handoff algorithm, a handoff attempt is initiated for this mobile (*Handoff/Handover Management*).

1.4 Need for power control

Most cellular radio systems either provide for the use of transmitter power control on the uplink and the downlink to reduce co-channel interference or have the capability to do so at the network operator's discretion. Interference management through power control also aids the system in providing each user an acceptable connection. The main idea is to adjust the power of each transmitter for a given channel allocation, such that the interference levels at the receiver locations are minimized. Maintaining adequate transmission quality is an obvious constraint. The purpose is not only to save valuable battery power in the terminals but also to avoid blocking of the base station receivers due to excessive received power.

At the terminal, transmitter power is at a premium since it comes from a battery. There is also a limit on the minimum and maximum transmitter power levels. We will be concerned with a control scheme that works under these constraints and achieves a specified minimum transmission quality for mobiles while conserving power. In practical systems, the efficacy of all power control strategies is limited by the accuracy of the signal and/or interference power estimates, and also the step size in transmitter power levels. The speed of the power adjustments determines how fast the schemes can adapt to the changes in the network due to fading, mobility, and traffic. Simulations under such constraints have been performed for the new soft dropping strategy and the results have displayed the improvement in performance over existing iterative power control schemes that meet SIR requirements..

1.5 Previous work

Initial work on transmitter power control schemes that achieve constant received power was reported in [1–3]. These schemes were based on the principle that the power should be reduced as the path gain (the negative path loss) is increased. Thus the received signal strength at the base station receiver is kept constant by compensating for the change in path gain. They also have the advantage that the dynamic range requirements for the receiver are smaller resulting in better adjacent channel protection. These schemes indicate an increase of system capacity by a factor of roughly equal to two relative to the schemes with constant transmitted power. A variation of this scheme is based on received signal strength, but the change in path gain is only partly compensated for. For this latter scheme it has been shown that there is some gain in capacity [4].

A centralized power control scheme that achieved a balance in SIR was presented in [5] for satellites employing frequency reuse. An iterative scheme that converged to the powers that achieved this SIR was described in [6]. The centralized SIR balancing concept was later applied to spread spectrum systems in [7]. Analysis in [8] has shown that large capacity gain is obtained by using a power control scheme that equalizes the quality throughout a channel to maximize the least SIR in the channel. The problem with such schemes is that the balanced SIR of all the mobiles in a channel may fall below the threshold when the channel is congested, rendering the channel unusable if every SIR in the channel is equalized. Another drawback was the need for centralized control in order to be stable. Thus practical implementation of such schemes in a cellular enviroment is difficult, even though they serve as a good norm for comparison to other schemes. The concept was further developed in [9] to derive a distributed scheme called the distributed balancing algorithm for TDMA/FDMA systems. In these schemes the SIR is controlled directly instead of controlling the received power. Similar work was proposed in [10] and [11] for centralized and distributed power control with the exception that the schemes compute the transmitter powers to affect the SIRs directly. In other words each mobile is assigned a transmitter power that adjusts its SIR to a common value. An algorithm that includes receiver noise power and achieves a target SIR for all terminals, if it is feasible, in a distributed way is presented in [15]. The use of variable SIR targets has been studied by simulation in [26] where it is found that the approach can yield significant performance improvements. References [18, 20, 22, 24] discuss work on integrated radio resource management.

1.6 Scope of the Thesis

This thesis provides a new power control scheme for radio networks and application of power control in the more general problem of radio resource management. The power control scheme developed here is one that is link quality based and distributed and asynchronous in nature. The link quality objective in every iteration depends on the current uplink transmitter power. We have provided convergence proofs for a single channel for this new power control technique. Practical implementation of the scheme at the base station is possible without any need for information from the neighboring base stations. In this work, we have attempted to evaluate the integration of the new power control scheme into existing radio resource management techniques on different systems, *viz.*, TDMA, GSM, and CDMA. The pertinent base station assignment, channel allocation and handoff/handover management schemes have been discussed. The communication on control channels is assumed to be error free and delay free.

The emphasis of this thesis is on the presentation of an improved variable target SIR power control scheme, introduced in [26], and a comprehensive study of its performance in simulated GSM and CDMA environments under some practical power control implementation constraints such as uplink transmitter power limits and step changes in power. The improvement in performance over schemes based on common SIR[1] targets is clearly affirmed by the simulation results. The principal finding of the results is that soft dropping does provide a considerable gain in capacity and an outstanding reduction in transmitter power without any significant loss in signal quality.

The thesis is organized as follows. The theoretical analysis for the new power control strategy is described in Chapter 2. In Chapter 3, the system model employed for simulation and the performance measures applied for subsequent discussion are described. In Chapter 4 simulation results for a TDMA or hybrid TDMA/FDMA are discussed with special reference to the Pan-European GSM system. Whereas simulation results for a spread spectrum-based CDMA system are evaluated and investigated in Chapter 5.

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[1]Every mobile adjusts its power to achieve a common SIR and to equalize the SIR throughout a channel.

Chapter 2

Soft dropping power control

In wireless communication systems, mobiles users adapt to a time varying radio channel by regulating transmitter powers. This power control is intended to provide each user an acceptable connection by eliminating unnecessary interference. Work in [19] unified and extended convergence results for cellular radio systems employing iterative power control methods. For a variety of systems it has been shown that interference constraints derived from the users' SIR requirements share certain simple properties. These properties imply that a power control algorithm converges not only synchronously but also totally asynchronously when users perform power adjustments with outdated or incorrect interference measurements.

This emphasis on meeting SIR constraints would appear to be particularly appropriate for the uplink of a CDMA system in which the unsynchronized signals of other users can be modeled as interfering noise signals. Previous analyses of power control have assumed fixed users' locations and time varying radio channel characteristics.

In [1, 5–8, 10, 15, 16], analytical approaches to attaining a common signal to interference ratio (SIR) or maximizing the minimum SIR throughout a channel are considered. The problem with this approach is that the balanced SIR of all the mobiles in a channel may fall below the threshold when there is congestion on the channel. In [19] several models for constrained, synchronous and totally asynchronous iterative power control schemes were considered. The uplink power control problem for the various models was reduced to finding a vector $\boldsymbol{p}$ of users' transmitter powers satisfying $\boldsymbol{p} \geq \boldsymbol{I}(\boldsymbol{p})$ where the jth constraint $p_j \geq I_j(\boldsymbol{p})$ describes the interference that user j must overcome to achieve an acceptable connection. In [17, 18, 20, 22, 24, 25], integrated approaches to power control and elements of radio resource management are considered.

Analytical methods have derived convergence results for iterative power control algorithms that meet SIR requirements. On occasion, it is not possible for every user to meet its SIR target. Such a situation is forced by an infeasible power control problem. When the power control problem is infeasible, no optimal solution exists for the power control problem. In the presence of maximum power constraints, some users will reach maximum transmitter power without achieving the target SIR [13, 14, 18, 20]. The sole reason for such a situation is the high interference introduced on the radio connection that makes it impossible for the mobiles on that channel to achieve the target quality and for some to even achieve the minimum quality requirement. This can result in dropped connections or additional handoffs to neighboring base stations.

In this work, we will attempt to deal with the negative implications of the infeasible power control situation on the performance of cellular system. The basic concept is that the target SIR is not a fixed value, but a variable one that ranges from maximum $\bar{\Gamma}$ to minimum $\hat{\Gamma}$. In particular, as a mobile raises its transmitted power, in response to either increased interference or reduced uplink gain, that mobile will lower its SIR target. That is, as we would normally approach an infeasible power control problem in which transmitter powers rapidly escalate, the variable target SIR algorithm encourages a user to aim for a lower SIR target to increase the likelihood that all users can be supported. Thus, when there is high interference at the base station, the power control strategy forces the terminals transmitting at high powers to aim for lower target SIRs in order to keep the co-channel interference in the system low. Since a user's target SIR gradually decreases as its transmitter power rises, we call this approach *soft dropping*. The algorithm is fully decentralized, in the sense that the only inputs to the algorithm are the signal to interference ratio, received power, and the interference measured at the receiver of the connection. Thus it can be implemented in the base station without requiring any information from other base stations. It is assumed in the analysis that the parameters necessary for performing soft dropping power control are accurate and available any time at the base or at the user's terminal.

2.1 Soft Dropping Interference Constraints

We will consider the uplink of a cellular communication system of n users in which signals of other users can be modeled as interfering signals. Let p_j denote the transmitter power of user j, and h_{kj} denote the propagation gain of user j to base k. At base k, the received signal power from user j is $h_{kj}p_j$ while the interference from all of users except user j is $\sum_{i \neq j} h_{ki}p_i + \sigma_k$ where σ_k denotes the receiver noise power at base k. Hence under power vector $\boldsymbol{p} = [p_1, \cdots, p_n]$, the SIR of user j at its assigned base station a_j can be written as

$$\gamma_j(\boldsymbol{p}) = \frac{p_j}{I_j(\boldsymbol{p})} \tag{2.1}$$

where

$$I_j(\boldsymbol{p}) = \frac{\sum_{i \neq j} h_{a_j i} p_i + \sigma_{a_j}}{h_{a_j j}} \tag{2.2}$$

Although we describe the users' link SIRs in the context of a fixed assignment of users to base stations, we will see that the soft dropping approach is applicable whenever each user's SIR can be expressed in the form of (2.1) for a standard interference function $\boldsymbol{I}(\boldsymbol{p}) = [I_1(\boldsymbol{p}), \cdots, I_n(\boldsymbol{p})]$; see [19].

In a fixed target power control algorithm, each user iteratively adjusts its power in order to find a power vector $\boldsymbol{p}$ such that for every user j,

$$\gamma_j(\boldsymbol{p}) \geq \Gamma_j \tag{2.3}$$

In the soft dropping power control algorithm, the SIR requirement of user j must satisfy

$$\gamma_j(\boldsymbol{p}) \geq \Gamma_j(p_j) \tag{2.4}$$

In this case, $\Gamma_j(p_j)$, the target SIR of user j, is varied according to the user's transmitter power p_j as depicted in Figure 1. Note that at all times, each user j aims for a target SIR that is above a common dropping threshold, Γ_d.

For $p_j \leq \bar{q}_j$, user j attempts to maintain a high quality connection by aiming for a target SIR $\overline{\Gamma}_j$. For $\hat{q}_j \leq p_j \leq p_j^{\max}$, user j aims for an acceptable target SIR $\hat{\Gamma}_j$. Note

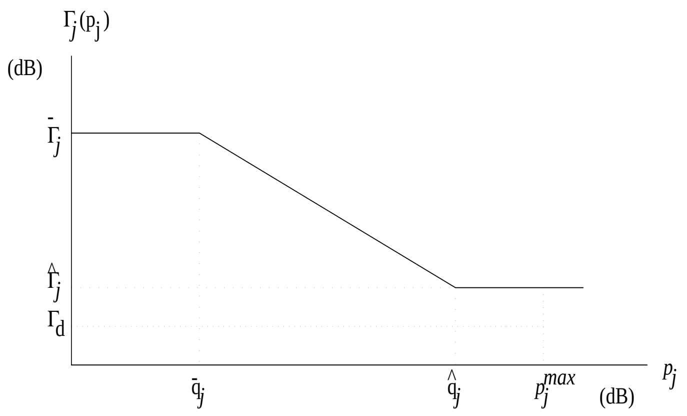

Figure 2.1: The variable SIR target $\Gamma_j(p_j)$

that $\overline{\Gamma}_j \geq \hat{\Gamma}_j \geq \Gamma_d$. For $\bar{q}_j < p_j < \hat{q}_j$, user j aims for a target SIR $\Gamma_j^{(v)}(p_j)$ that trades SIR for transmitter power linearly in dB.

We observe that a fixed SIR target iterative algorithm [13] can be written as

$$p_j(t+1) = \left(\frac{\Gamma_j}{\gamma_j(\boldsymbol{p}(t))}\right)^{\beta_j} p_j(t) \tag{2.5}$$

where β_j is an arbitrary constant satisfying $0 < \beta_j \leq 1$. Note that when $\beta_j = 1$ as in [13], we have $p_j(t+1) = \Gamma_j I_j(\boldsymbol{p}(t))$. In this case, user j iteratively chooses the power $p_j(t+1)$ that would provide exactly SIR Γ_j if all other users held their transmitter powers constant. That is, when user j has SIR $\gamma_j(\boldsymbol{p})$ that is less than Γ_j, user j raises its transmitter power. Conversely, when the SIR of user j is above the target Γ_j, user j lowers its power. The effect of the exponent β_j can be seen by expressing the power control iteration in logarithmic terms. From (2.5), we can write

$$\log p_j(t+1) = (1-\beta_j)\log p_j(t) + \beta_j \log\left(\Gamma_j I_j(\boldsymbol{p}(t))\right) \tag{2.6}$$

For $0 < \beta_j < 1$, we see that in dB, user j chooses a weighted average of its current transmitter power $p_j(t)$ and the necessary power $\Gamma_j I_j(\boldsymbol{p}(t))$ for SIR Γ_j. Typically, we will see in simulations that small β_j results in slow convergence of the power control algorithm.

By replacing the fixed SIR target, Γ_j, of (2.5) and (2.6) with the variable SIR target,

$\Gamma_j(p_j)$, the iterative variable target SIR scheme can be expressed in the following forms:

$$p_j(t+1) = \left(\frac{\Gamma_j(p_j)}{\gamma_j(\boldsymbol{p}(t))} \right)^{\beta_j} p_j(t) \tag{2.7}$$

$$\log p_j(t+1) = (1-\beta_j) \log p_j(t) + \beta_j \log \left(\Gamma_j(p_j) I_j(\boldsymbol{p}(t)) \right) \tag{2.8}$$

Similar to [18] we can express the variable SIR target iteration in (2.7) as

$$\boldsymbol{p}(t+1) = \boldsymbol{T}(\boldsymbol{p}(t)) \tag{2.9}$$

where, from (2.1),

$$T_j(\boldsymbol{p}) = \left(\frac{\Gamma_j(p_j)}{\gamma_j(\boldsymbol{p})} \right)^{\beta_j} p_j = (\Gamma_j(p_j))^{\beta_j} p_j^{1-\beta_j} I_j^{\beta_j}(\boldsymbol{p}) \tag{2.10}$$

At this point, it is not clear that the iteration (2.9) will converge. In particular, it is easy to imagine oscillatory effects in which user j has low transmitted power and aims for high SIR, leading user j to have high power and aim for low SIR resulting in low transmitter power. However, as we shall see, in the context of soft dropping power control algorithm, the dB averaging effect of β_j will be necessary for curbing such oscillatory behavior. Typically, we will also see in simulations that small β_j for the iteration (2.9) results in slow convergence of the power control algorithm.

Finally, it will be desirable to consider minimum and maximum power limits $\boldsymbol{p}^{\min} = [p_1^{\min}, \cdots, p_n^{\min}]$ and $\boldsymbol{p}^{\max} = [p_1^{\max}, \cdots, p_n^{\max}]$. We define the constrained iteration $\boldsymbol{T}^*(\boldsymbol{p})$ by

$$\boldsymbol{T}_j^*(\boldsymbol{p}) = \max \left\{ p_j^{\min}, \min \left\{ p_j^{\max}, T_j(\boldsymbol{p}) \right\} \right\} \tag{2.11}$$

In this case, $\boldsymbol{p}^{\min} \leq \boldsymbol{T}^*(\boldsymbol{p}) \leq \boldsymbol{p}^{\max}$. Whenever the iteration function $\boldsymbol{T}(p)$ would require a power over the maximum or under the minimum, the power chosen is constrained. We will show that the constrained variable SIR target power control iteration

$$\boldsymbol{p}(t+1) = \boldsymbol{T}^*(\boldsymbol{p}(t)) \tag{2.12}$$

will always converge to a unique fixed point at which each user's variable SIR target will be met subject to the minimum and maximum power constraints.

2.2 Standard Interference Functions

To verify convergence of the iteration (2.12), we will use the approach of standard interference functions in [18] in which the users SIR requirements are expressed in terms of a set of vector interference constraints

$$\boldsymbol{p} \geq \boldsymbol{I}(\boldsymbol{p}) \tag{2.13}$$

That is, if under power vector $\boldsymbol{p}$, $p_j \geq I_j(\boldsymbol{p})$, then user j has SIR that meets or exceeds its target SIR. For the uplink of a variety of single channel cellular systems, the interference function $\boldsymbol{I}(\boldsymbol{p})$ was shown to be *standard* in the following sense.

Definition 1 *$\boldsymbol{I}(\boldsymbol{p})$ is a standard interference function if for all $\boldsymbol{p} \geq 0$, the following properties are satisfied.*

- *(Positivity)* $\boldsymbol{I}(\boldsymbol{p}) > 0$
- *(Monotonicity) If $\boldsymbol{p} \geq \boldsymbol{p}'$, then $\boldsymbol{I}(\boldsymbol{p}) \geq \boldsymbol{I}(\boldsymbol{p}')$*
- *(Scalability) For all $\alpha > 1$, $\alpha \boldsymbol{I}(\boldsymbol{p}) > \boldsymbol{I}(\alpha \boldsymbol{p})$*

Given a standard interference function $\boldsymbol{I}(\boldsymbol{p})$, the iteration

$$\boldsymbol{p}(t+1) = \boldsymbol{I}(\boldsymbol{p}(t)) \tag{2.14}$$

was called a *standard* power control algorithm and the following claim was verified.

Theorem 1 *If there exists a power vector $\boldsymbol{p}'$ satisfying the feasibility condition $\boldsymbol{p}' \geq \boldsymbol{I}(\boldsymbol{p}')$, then starting from any initial power vector $\boldsymbol{p}$, the standard power control iteration converges to a unique fixed point $\boldsymbol{p}^*$ such that $\boldsymbol{p}^* \leq \boldsymbol{p}'$ for any feasible power vector $\boldsymbol{p}'$.*

The consequence of Theorem 1 is that for any function $\boldsymbol{T}(\boldsymbol{p})$ that meets the requirements of a standard interference function, the iteration $\boldsymbol{p}(t+1) = \boldsymbol{T}(\boldsymbol{p}(t))$ is guaranteed to converge whenever $\boldsymbol{p} \geq \boldsymbol{T}(\boldsymbol{p})$ has a feasible solution. We emphasize that $\boldsymbol{T}(\boldsymbol{p})$ need not represent the actual SIR constraints of the users.

We will also need results regarding the componentwise minimum and maximum of two interference functions. Specifically, given two standard interference functions $\boldsymbol{I}(\boldsymbol{p})$ and $\boldsymbol{I}'(\boldsymbol{p})$, we define $\boldsymbol{I}^{\max}(\boldsymbol{p})$ and $\boldsymbol{I}^{\min}(\boldsymbol{p})$ by

$$\boldsymbol{I}_j^{\max}(\boldsymbol{p}) = \max\left\{\boldsymbol{I}_j(\boldsymbol{p}), \boldsymbol{I}'_j(\boldsymbol{p})\right\} \tag{2.15}$$

$$\boldsymbol{I}_j^{\min}(\boldsymbol{p}) = \min\left\{\boldsymbol{I}_j(\boldsymbol{p}), \boldsymbol{I}'_j(\boldsymbol{p})\right\} \tag{2.16}$$

The following claim is readily verified.

Theorem 2 *If $\boldsymbol{I}(\boldsymbol{p})$ and $\boldsymbol{I}'(\boldsymbol{p})$ are monotone and scalable, then $\boldsymbol{I}^{\min}(\boldsymbol{p})$ and $\boldsymbol{I}^{\max}(\boldsymbol{p})$ are monotone and scalable.*

Note that when $\boldsymbol{I}(\boldsymbol{p}) = \boldsymbol{r}$ where $\boldsymbol{r}$ is a positive constant vector, it is trivially true that $\boldsymbol{I}(\boldsymbol{p})$ is a standard interference function. Thus, Theorem 2 has the following corollary,

Corollary 1 *For positive power vectors $\mathbf{p}^{\min}$ and $\mathbf{p}^{\max}$ and a scalable and monotone interference function $\boldsymbol{I}(\mathbf{p})$, $\boldsymbol{I}''(\boldsymbol{p})$ defined by*

$$I''_j(\boldsymbol{p}) = \max\left(p_j^{\min}, \min\left(p_j^{\max}, I_j(\boldsymbol{p})\right)\right) \tag{2.17}$$

is a standard interference function. Since $\mathbf{p}^{\max} \geq \boldsymbol{I}''(\boldsymbol{p}^{\max})$, the iteration $\mathbf{p}(t+1) = \boldsymbol{I}''(\boldsymbol{p}(t))$ always converges to a unique fixed point.

2.3 Soft Dropping Power Control Convergence

In this section, we analyze the synchronous constrained power control iteration (2.12) in which users repeatedly adjust their transmitter powers to meet the variable target SIR constraints (2.4). From Figure 2.1, the variable target SIR $\Gamma_j(p_j)$ can be written

$$\Gamma_j(p_j) = \begin{cases} \overline{\Gamma}_j & p_j \leq \bar{q}_j \\ \Gamma_j^{(v)}(p_j) & \bar{q}_j < p_j < \hat{q}_j \\ \hat{\Gamma}_j & p_j \geq \hat{q}_j \end{cases} \tag{2.18}$$

From (2.10) and (2.18), we can write the following:

$$T_j(\boldsymbol{p}) = \begin{cases} \overline{T}_j(\boldsymbol{p}) & p_j \leq \bar{q}_j \\ T_j^{(v)}(\boldsymbol{p}) & \bar{q}_j < p_j < \hat{q}_j \\ \hat{T}_j(\boldsymbol{p}) & p_j \geq \hat{q}_j \end{cases} \tag{2.19}$$

where,

$$\overline{T}_j(\boldsymbol{p}) = \overline{\Gamma}^{\beta_j} p_j^{1-\beta_j} I_j^{\beta_j}(\boldsymbol{p}) \tag{2.20}$$

$$T_j^{(v)}(\boldsymbol{p}) = (\Gamma_j^{(v)}(p_j))^{\beta_j} p_j^{1-\beta_j} I_j^{\beta_j}(\boldsymbol{p}) \tag{2.21}$$

$$\hat{T}_j(\boldsymbol{p}) = \hat{\Gamma}^{\beta_j} p_j^{1-\beta_j} I_j^{\beta_j}(\boldsymbol{p}) \tag{2.22}$$

To specify $\boldsymbol{T}^{(v)}(\boldsymbol{p})$ completely, we observe from Figure 2.1 that the slope of $\Gamma_j^{(v)}(p_j)$ equals $-\delta_j$ where

$$\delta_j = \frac{\log(\overline{\Gamma}_j/\hat{\Gamma}_j)}{\log(\hat{q}_j/\bar{q}_j)} \tag{2.23}$$

Moreover, from Figure 2.1, we see that $\Gamma_j^{(v)}(p_j)$ satisfies

$$\log \Gamma_j^{(v)}(p_j) = \log \overline{\Gamma}_j - \delta_j(\log p_j - \log \bar{q}_j) \tag{2.24}$$

We can express the above equation as,

$$\Gamma_j^{(v)}(p_j) = \overline{\Gamma}_j p_j^{-\delta_j} \bar{q}_j^{\delta_j} \tag{2.25}$$

From (2.21) and (2.25), we have

$$T_j^{(v)}(\boldsymbol{p}) = \overline{\Gamma}_j^{\beta_j} \bar{q}_j^{\beta_j \delta_j} p_j^{1-\beta_j(1+\delta_j)} I_j^{\beta_j}(\boldsymbol{p}) \tag{2.26}$$

To prove convergence of the iteration (2.12), we will need the following lemmas.

Lemma 1 *If $\boldsymbol{I}(\boldsymbol{p})$ is standard, then $\boldsymbol{I}'(\boldsymbol{p})$ defined by $I_j'(\boldsymbol{p}) = c_j p_j^{\mu_j} I_j^{\beta_j}(\boldsymbol{p})$ is scalable and monotone if for all j, $c_j > 0$, $\beta_j > 0$, $\mu_j \geq 0$, and $\mu_j + \beta_j \leq 1$.*

Proof: Lemma 1 To check monotocity, we note that, $\boldsymbol{p} \geq \boldsymbol{p}'$ implies $I_j^{\beta_j}(\boldsymbol{p}) \geq I_j^{\beta_j}(\boldsymbol{p}')$ and $p_j^{\mu_j} \geq \left(p_j'\right)^{\mu_j}$.

Thus,

$$I'_j(\boldsymbol{p}) = c_j p_j^{\mu_j} I_j^{\beta_j}(\boldsymbol{p}) \geq c_j \left(p'_j\right)^{\mu_j} I_j^{\beta_j}(\boldsymbol{p}') = I'_j(\boldsymbol{p}') \tag{2.27}$$

To verify scalability, observe that for all $\alpha > 1$,

$$\begin{aligned} \alpha I'_j(\boldsymbol{p}) &\geq c(\alpha p_j)^{\mu_j} \left(\alpha I_j(\boldsymbol{p})\right)^{\beta_j} && (2.28) \\ &> c(\alpha p_j)^{\mu_j} I_j^{\beta_j}(\alpha \boldsymbol{p}) && (2.29) \\ &= I'_j(\alpha \boldsymbol{p}) && (2.30) \end{aligned}$$

□

From Lemma 1, we have the following corollary.

Theorem 3 *If $0 \leq \beta_j \leq (1+\delta_j)^{-1}$ for all j, the interference functions $\hat{\boldsymbol{T}}(\boldsymbol{p})$, $\boldsymbol{T}^{(v)}(\boldsymbol{p})$ and $\overline{\boldsymbol{T}}(\boldsymbol{p})$ are all scalable and monotone.*

As a consequence of Lemma 1, we now can prove the following claim.

Theorem 4 *The power control iteration function $\boldsymbol{T}(\boldsymbol{p})$ defined by (2.10) is scalable and monotone.*

Proof: Theorem 4 Note that (2.20) and (2.26) imply

$$T_j^{(v)}(\boldsymbol{p}) = \left(\frac{\bar{q}_j}{p_j}\right)^{\beta_j \delta_j} \overline{T}_j(\boldsymbol{p}) \tag{2.31}$$

Since (2.20) and (2.22) imply $\overline{T}_j(\boldsymbol{p}) = (\overline{\Gamma}_j/\hat{\Gamma}_j)^{\beta_j} \hat{T}_j(\boldsymbol{p})$, we can write

$$T_j^{(v)}(\boldsymbol{p}) = \left(\frac{\bar{q}_j}{p_j}\right)^{\beta_j \delta_j} \left(\frac{\overline{\Gamma}_j}{\hat{\Gamma}_j}\right)^{\beta_j} \hat{T}_j(\boldsymbol{p}) \tag{2.32}$$

Since (2.23) implies $\overline{\Gamma}_j/\hat{\Gamma}_j = (\hat{q}_j/\bar{q}_j)^{\delta_j}$, (2.32) permits us to write

$$T_j^{(v)}(\boldsymbol{p}) = \left(\frac{\hat{q}_j}{p_j}\right)^{\beta_j \delta_j} \hat{T}_j(\boldsymbol{p}) \tag{2.33}$$

Thus, from (2.31) and (2.33), we observe that

$$T_j^{(v)}(\boldsymbol{p}) \leq \overline{T}_j(\boldsymbol{p}) \quad \text{iff} \quad p_j \geq \bar{q}_j \tag{2.34}$$

$$T_j^{(v)}(\boldsymbol{p}) \leq \hat{T}_j(\boldsymbol{p}) \quad \text{iff} \quad p_j \geq \hat{q}_j \tag{2.35}$$

From (2.19), this implies that the iteration function $\boldsymbol{T}(\boldsymbol{p})$ can be written as

$$T_j(\boldsymbol{p}) = \max\left\{\hat{T}_j(\boldsymbol{p}), \min\left\{\overline{T}_j(\boldsymbol{p}), T_j^{(v)}(\boldsymbol{p})\right\}\right\} \tag{2.36}$$

By Theorem 2, we see that $\boldsymbol{T}'(\boldsymbol{p})$ defined by $T_j'(\boldsymbol{p}) = \min\left\{\overline{T}_j(\boldsymbol{p}), T_j^{(v)}(\boldsymbol{p})\right\}$ is scalable and monotone and thus $T_j(\boldsymbol{p}) = \max\left\{T_j'(\boldsymbol{p}), \hat{T}_j(\boldsymbol{p})\right\}$ is also scalable and monotone. □

As a consequence of Theorem 4 and Corollary 1, we have the following corollary.

Corollary 2 *The constrained iteration function $\boldsymbol{T}^*(\boldsymbol{p})$ defined by (2.11) is a standard interference function.*

Thus, the power constrained iteration (2.12) always converges to a unique fixed point at which each user transmits with the minimum possible transmitted power subject to variable target SIR requirements.

Chapter 3

Simulation Model and Performance measures

The convergence analysis of Chapter 2 is valid for a single channel system. In this chapter, we will discuss the simulation model employed to create the appropriate real world environment for study and discussion of the new power control strategy. The performance of an asynchronous, distributed soft dropping power control algorithm in a channelized system is evaluated by simulation of a two dimensional macro-cellular system.

We will investigate the application of the strategy to not only an instance of TDMA/FDMA systems but also to that of an instance of spread spectrum systems such as CDMA, where dramatic improvements have been observed. The differences in the simulation model employed for the two broad categories of cellular systems, *viz.,* TDMA and CDMA, can be referred to in Table 5.1. Base station assignment and channel allocation schemes along with various handoff algorithms are also simulated to study the impact of this algorithm on radio resource management in a cellular system environment. A simulation environment in which the mobile users not only suffer from distance propagation loss but also shadow fading is employed.

Using this simulation environment we examine the performance of the new power control algorithm in terms of statistics described in Section 3.7. In order to assess the performance improvement of soft dropping, these statistics are compared with those of ordinary fixed target power control[1] algorithm in a similar environment. The discussion of results will be restricted to the uplink (mobile to base station) connection.

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[1]common target SIR and fixed target SIR power control are names used interchangeably.

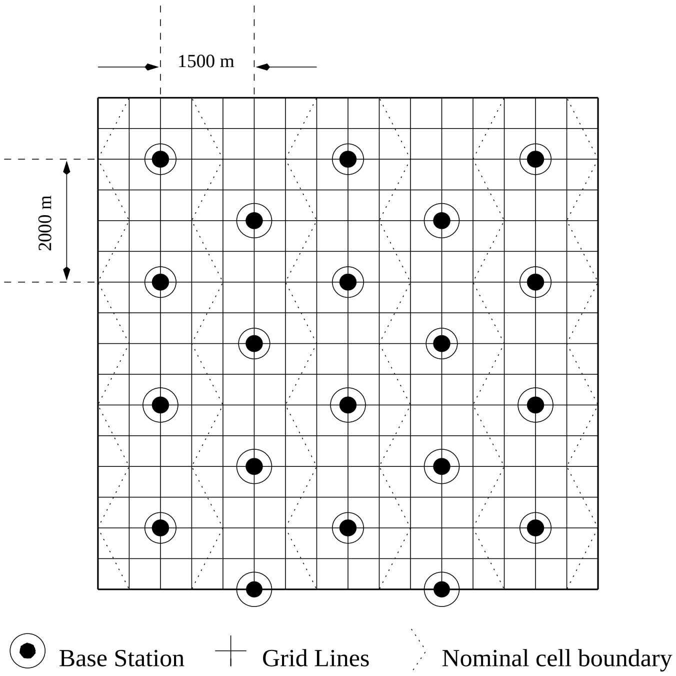


Figure 3.1: Two-dimensional macro-cell environment

3.1 Cell Layout

For simulation of a two dimensional macro cellular system, we assume a Manhattan-like road grid structure which is formed into a torus-like structure to avoid edge effects. As shown in Figure 3.1, $B = 20$ base stations are spaced uniformly. Each cell has a base station located at the center of the cells with an omni directional antenna of height 50 m. All the base stations are spaced 2000 m apart vertically and 1500m horizontally on the torus. In the model the nominal shape of each cell is hexagonal; however, the actual cell boundary will depend on the spatially correlated shadow fading (Section 3.4). In addition the grid lines on the system layout (Figure 3.1) are streets (East-West) and avenues (North-South). In simple words, every horizontal grid line is a street and every vertical grid line is an avenue. Also, a set of specified channels are available on each base station.

3.2 Call Traffic parameters

The new call arrival process is an independent Poisson process with mean arrival rate λ calls per second, uniformly distributed over the entire torus. Call durations are independent exponential random variables with mean $1/\mu$=120 sec. With B base stations and M channels/cell, the normalized traffic load is $\rho = \lambda/(\mu \text{MB})$ Erlangs/cell/channel.

3.3 Mobility model

A mobile's speed follows a truncated Gaussian distribution with mean speed of 90 km/hr and standard deviation of 15 km/hr, truncated at a minimum speed of 60 km/hr and maximum speed of 120km/hr ($\pm 2\sigma$). The new call arrivals are uniformly distributed on all the roads and the two directions along the road are equally likely. Traffic is allowed only along the grid lines, to avoid complexity. Free flowing highway traffic is assumed, in other words each mobile moves along the road unaware of any other mobile on the same path. The velocity of the mobile, once decided at the origination of a call, remains fixed throughout the duration of a call. The direction of movement of the mobile, is however probabilistic once it reaches the intersection of two grid lines. There are three possibilities once it reaches a cross. At an intersection; the mobile goes straight with a probability 0.6 and turns in either direction with probability 0.2.

3.4 Propagation Model

The signal strength depends not only on the distance from the transmitter, but also on the various details of the physical environment around the transmitter and receiver, such as terrain, buildings, and other obstacles in the signal path. The received signal strength at the mobile is therefore calculated as the emitted power less path loss between the base and the mobile. The radio link gain includes both a distance propagation loss model of order $\alpha = 4$ and lognormal shadow fading. The link gain h_{kj} from the mobile

j at a distance d_{kj} to base k in units of dB is

$$10 \log h_{kj} = -10\alpha \log d_{kj} + S_j(d_{kj}) \tag{3.1}$$

where $S_j(d_{kj})$, the position dependent shadow fading factor, is modeled as a zero mean Gaussian random variable with standard deviation $\sigma = 6$ dB. The shadow fading processes $S_j(d)$ and $S_{j'}(d')$ for distinct base stations j and j' are assumed to be independent. To account for the autocorrelation of the shadow fading over distance, we use a first order autoregression model. A shadow fading pattern is thus generated by applying the autoregressive model over the streets and the avenues of the simulated system. The correlation distance, D, is 50m and shadow fading measurements are obtained at Δd = 20m intervals. The autocorrelation of the shadow fading process is modeled as

$$R_{S_\sigma}(\Delta d) = \sigma^2 e^{-\Delta d/D} \tag{3.2}$$

If signal strength measurements are taken at equally spaced locations, $d_n = n\Delta d$ for N points on a grid line, i.e., $d_1, d_2, d_3, \cdots, d_N$, we have

$$S_\sigma(d_i) = e^{-\Delta d/D} S_\sigma(d_{i-1}) + V_i \tag{3.3}$$

where V_i are the independent and identically distributed normal random variables with

$$E[V_i] = 0 \tag{3.4}$$

$$E[V_i^2] = \sigma^2(1 - e^{-2\Delta d/D}) \tag{3.5}$$

3.5 Handoff Algorithms

Mobility of the users places strong demands on cellular systems in the form of fast and reliable handoffs. Previous work has been done on handoff algorithms based on received signal strength index (RSSI) and received power based handoff schemes. References [28–30] study the RSSI based handoff process itself and [31–33] investigated it's effect on system performance and capacity. RSSI based handoff schemes use only path loss information in making handoff decisions and thus do not respond to traffic density. Small values of RSSI hysteresis, h, could lead to a "ping-pong" effect and variation

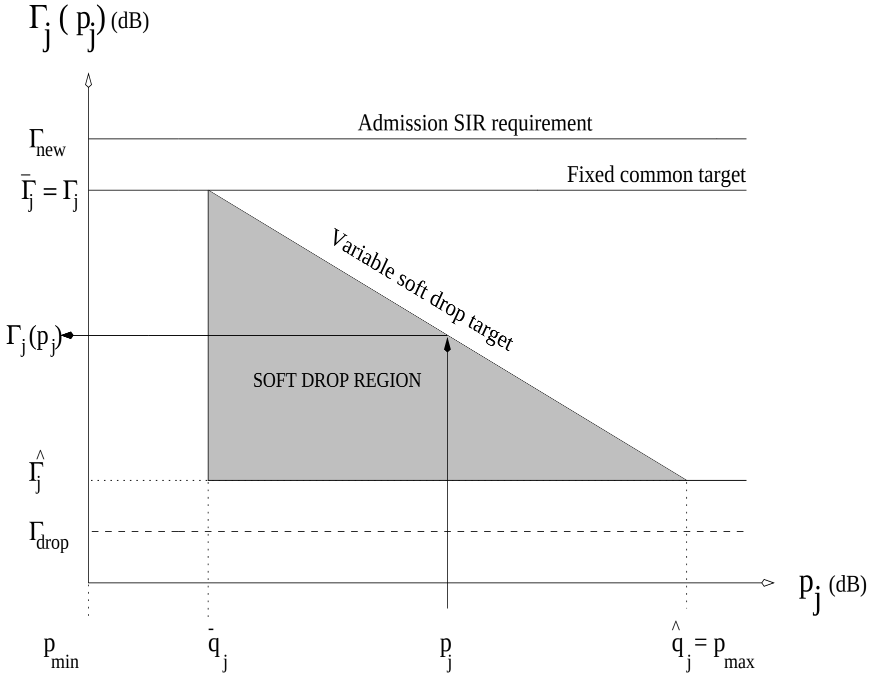


Figure 3.2: Soft drop region for power control

in average handoff distance. Received power based handoff scheme – minimum power handoff algorithm with a handoff timer [23] allow the mobiles to constantly search for a combination of base and channel assignment that minimizes the uplink transmitter power. We will provide a comparison of the performance of soft dropping with various handoff schemes.

3.6 Soft Dropping Parameters

In the fixed target power control scheme, each active user in the system aims for the SIR target, Γ_j, irrespective of its current transmitter power as shown in Figure 3.2. In other words, the target SIR remains fixed for the whole range of possible transmitter powers for every terminal leading to increased interference at the base on a particular channel.

The crux of the methodology employed to deal with the implications of fixed target SIR based schemes lies in encouraging the users to aim for lower target SIRs as they raise their transmitter powers. In other words, the users should start being less ambitious and more accommodating by aiming for lower target SIRs as they approach the problem of infeasibility. Thus there are two primary issues that will influence the impact of the new algorithm; the first is that of the range of uplink transmitter powers over which the user aims for lower target SIRs and the second is the range of target SIRs that the user aims for during the period it is in the soft drop region (Figure 3.2). Thus, for soft dropping, there exist two sets of limits, each defining the range of target SIRs and uplink transmitter powers. The importance of the values of these constraints will be clearly evident in the simulation results in Chapters 4 and 5. The limits for definition of the range of target SIRs (Figure 3.2), $\overline{\Gamma}_j$ and $\hat{\Gamma}_j$, are both fixed to values that are above the minimum requirement, Γ_d. The upper limit on target SIR, $\overline{\Gamma}_j$, is such that ideally we would like all the mobile users to be at the minimum power and aiming for a target SIR that is equal to Γ_j. The soft drop target SIR threshold, $\hat{\Gamma}_j$, is set sufficiently higher than the minimum requirement so that even in the worst situation when the transmitter powers are at the maximum constraints, P_m, a mobile will aim for a target SIR that is above the minimum signal quality requirement, Γ_d. There exists a trade-off in the performance of the system with the two set of parameters. Large range between the two transmitter power limits leads to a considerable reduction in the transmitter power levels, however it is also responsible for a deterioration in the quality of connection achieved by the mobile users at high loads, as will be observed in the simulation results discussed in the following chapters.

3.7 Performance Measures

The system performance is measured in terms of the following parameters for the whole simulation time:

- Call blocking,

$$P_b = \frac{\text{Number of new calls blocked}}{\text{Number of calls arrived}} \tag{3.6}$$

- Call dropping,

$$P_d = \frac{\text{Number of calls dropped}}{\text{Number of calls that were admitted}} \tag{3.7}$$

- Combined performance in terms of P_b and P_d. Since dropping an existing call is sometimes more annoying to the user than blocking a call. Hence we have also considered a weighted service denial rate $P_b + 10P_d$.

The empirical distributions of the uplink SIRs and the uplink transmitter powers of the mobile users is the snapshot of all the active terminals' current uplink SIR and transmitter power. We will use these distributions to measure the average uplink transmitter power level and the quality (SIR) achieved for the connection. We will discuss the performance improvements of soft dropping over conventional fixed target power control algorithm with two distinct handoff algorithms, *viz.* RSSI based, and minimum interference based handoff schemes. Each algorithm is simulated with different parameters relevant to the cellular system technology under simulation, to study and analyze the effect on the overall system performance.

Chapter 4

Soft dropping for a TDMA/FDMA system

The Pan-European Global System for Mobile (GSM) is a second generation cellular system standard that was developed to solve the fragmentation problems of the first cellular systems in Europe. It is the world's first cellular system to specify digital modulation and network level architectures and services and presently also the world's most popular standard for new cellular radio and personal communications equipment throughout the world. While there are several similarities between the GSM and the North American digital systems, GSM stands apart in two respects. It is a purely digital system. There is no provision for dual-mode operation with an analog system. The difference reflects the contrast between the diversity of analog cellular systems in Europe and the ubiquitous deployment of AMPS systems in North America. Another difference is the large number of network interfaces specified by GSM, in contrast with the CDMA standard and NA-TDMA standard which specify only the air interface.

In this chapter we have however attempted to simulate only the basic cellular radio network in a specified area with appropriate radio resource management schemes that utilize the information available to perform its task. The chapter can be broadly divided into two parts; the first half gives a brief overview of the GSM system in addition to discussing the radio resource management techniques that are employed in our model to simulate the same (Sections 4.1, 4.2, and 4.3), whereas the second half of the chapter will provide a complete analysis for results of the simulation (Section 4.4). The cell layout (Figure 3.1), call traffic parameters, mobility model and the propagation models remain the same as discussed in Chapter 3.

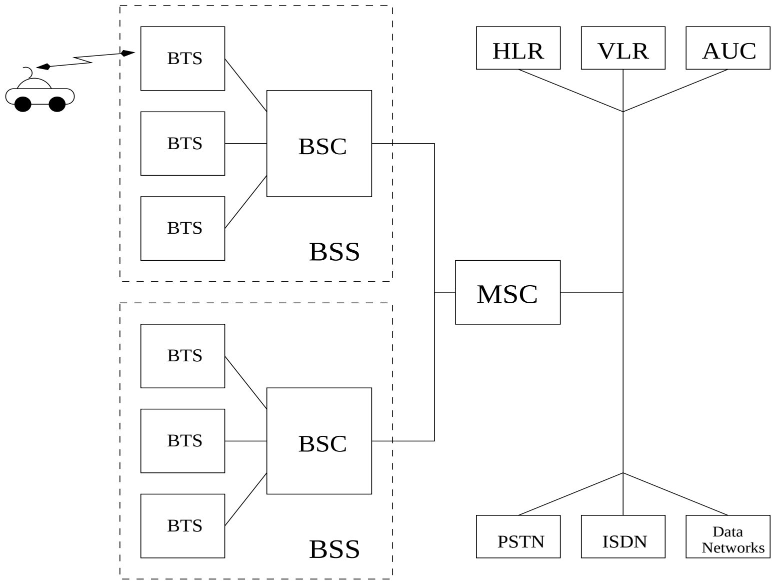


Figure 4.1: GSM System Architecture

4.1 Network Architecture

The GSM network architecture (Figure 4.1) consists of three essential network elements: mobile station (MS), base station (BS), and the mobile switching center (MSC). In addition, GSM specifies three databases, home location registers (HLR), visitor location registers (VLR), and authentication center (AUC). The HLR and VLR are elements serving the purpose of mobility management. In keeping with the preference of the GSM service industry for a large number of open interfaces, GSM specifies cellular base stations in more detail than any other system. GSM defines distinct base transceiver stations (BTS) consisting primarily of radio equipment, and base site controllers (BSC), that perform network control operations and signal processing functions. Typically, one BSC controls several BTSs.

4.2 Radio Transmission

GSM uses frequency division duplex and a combination of TDMA and frequency hopped multiple access (FHMA) schemes to provide base stations with simultaneous access to multiple users. The available forward and reverse frequency bands are divided into 200 kHz wide channels called ARFCNs (absolute radio frequency channel numbers). The combination of a time slot and an ARFCN constitutes a *physical channel* for both the uplink and the downlink. Each physical channel in a GSM system can be mapped into different *logical channels* at different times, that is, each specific time slot or frame may be dedicated to either handling traffic data, signaling data (required by the internal workings of the GSM system), or control channel data (from the MSC, base station, or mobile user). The TDMA structure consists of a hierarchy of frame types in which the traffic channels (TCH) and a variety of control channels (CCH) are defined [41, 51]. However we will not account for signaling messages in the simulation model. Narrowband FDMA channels are assumed to be orthogonal, hence mobiles using different channels do not interfere with each other.

4.3 Radio Resource Management in GSM

The radio resource management aspect of GSM systems consists of the ubiquitous elements of any integrated radio resource management technique applied to a FDMA/TDMA system; base station assignment, admission control and subsequent channel allocation, transmitter power control and handover management.

A new call in GSM system is connected to the base station with the strongest pilot tone on the broadcast control channel. The base station then attempts to allocate a pair of frequency band to communicate on. The control of the transmitted power on the radio path aims at minimizing average power broadcast by mobile stations as well as by base stations, whilst keeping transmission quality above a given threshold. Every time a new cell is entered, the radio channel (frequency band) used for the call may also change. To offer a good service quality that is independent of one's geographical location and mobility, the handover operation must meet some requirements. In this section we will discuss the various strategies employed for implementation of radio resource management, *viz.*, base station assignment (Section 4.3.1), admission control and channel allocation (Section 4.3.2), power control (Section 4.3.3) and handover management (Section 4.3.4).

4.3.1 Base Station Assignment

One natural thought for a new call base station assignment is to assign the mobile to the geographically nearest BS. However, in a real system, the geographic location of a new call is practically impossible to find. Because of shadow fading and co-channel interference properties of a cellular environment, the nearest base station may not provide the best communications link to the mobile user. A better way is to assign the BS to which the user has the highest gain. We also assume that the base stations are constantly transmitting a pilot tone on the downlink at a certain constant power P_c which is known to all the users. The new user listens to all the BSs and compares the strength of each pilot tone to decide to which one it should connect. The mobile user j is assigned to the BS with the strongest received pilot tone,

$$\text{Base station } k \text{ of mobile user } j = \arg \max_{k \in B} (P_c h_{kj}) \tag{4.1}$$

where P_c is the transmit power of pilot signal which is the same for all the base stations, h_{kj} is the gain factor due to path loss and fading between the mobile user j and base station k, and B is the set of base stations in the system.

4.3.2 Admission Control and Channel Allocation

Efficient channel reuse is of prime importance in the design of high capacity cellular radio networks. Cochannel interference caused by frequency reuse is the single most restraining factor on the system capacity. Systems may be designed either to tolerate low SIRs (i.e., efficient modulation and coding schemes), or to reduce the interference with efficient cell planning. In addition, dynamic channel allocation (DCA) may be used to reduce the interference even more by adapting the cell plan to changing traffic and unforeseen propagation conditions [24]. Using DCA algorithms to select communications channels as needed, TDMA or FDMA systems can serve dynamic and nonuniform traffic demands [46]. Under the assumption of real-time central processing of interference information, [45] demonstrated that significant capacity improvement could be gained using this class of assignment methods. Work on distributed DCA algorithms in [47,48] has shown promising results in improving spectrum efficiency with reduced complexity. The channel assignment we will be concerned with, is based on signal strength measurements in a distributed manner and therefore gives an improvement in capacity over schemes using reuse distance criterion for channel assignment. Since only the uplink is considered, the following procedure for channel assignment is assumed. When a terminal needs a channel, it signals to a base station with the strongest signal. The base station k measures the signal interference $I_i^{(k)}$ on each unoccupied channel i to decide which channel to assign to the mobile user j. The channel with the least signal interference, that is the channel h such that

$$h = \arg \min_{i \in C_k} (I_i^{(k)}) \tag{4.2}$$

where C_k is the set of channels at base station k that are unoccupied.
The minimum interference scheme is a well known scheme among the simplest schemes for channel allocation. It is incorporated in the CT-2 (Enhanced Cordless Phone) and the DECT (Pan-European Cordless Phone) systems ([44,49–51]). This is a distributed scheme since the base station makes the decision based on local measurements. The channel assignment is done for a set of terminals frozen at their respective positions. So the channel assignment here does not take the movement of the users into consideration. The ease of implementation and flexibility of the distributed dynamic channel assignment scheme makes it attractive for cellular systems. A terminal can fail admission to the system in two ways,

- the base station is unable to find a free channel in the spectrum at its disposal,
- the mobile user is alloted a channel that carries minimum signal interference but it is unable to achieve the minimum SIR requirement, Γ_{new}, for a new call due to insufficient transmitter power to overcome either,

- interference, $I_i^{(k)}$, that is too high, and/or
- extremely low path gain h_{kj}.

The SIR requirement, Γ_{new}, for any incoming call was kept higher than the target SIR, Γ_j, in the simulations. The algorithm thus provides protection from a situation where the admission of the new mobile user could could cause other terminals already on that channel to have an SIR below the minimum quality requirements, Γ_{drop}.

4.3.3 Power control

In GSM, both uplink and downlink power control may be applied independently one from the other; furthermore they are applied independently with each mobile station [42]. In order to transport signaling data in parallel with the transmission of a user data flow, GSM offers an associated low rate channel: the SACCH (Slow Associated Control CHannel) along with each traffic channel. This bi-directional channel can carry a message every 480 ms in each direction, with a transmission delay of about half a second. The RF power level to be employed by the MS is indicated by means of the 5 bit **TXPWR** field sent in the layer 1 header of the downlink SACCH message block [43]. The range specified for uplink power control lies between 20 and 30 dB, by steps of 2 dB, depending on the mobile station power class. A command to change the transmission power does not trigger an immediate transition to the ordered value in the MS. The maximum variation speed is of 2 dB each 60 ms. This means in particular that a high jump (more than 12 dB) will not be terminated when the next command arrives on the SACCH. The range used for the downlink power control is manufacturer dependent and may be up to 30 dB, also by steps of 2 dB. The control of the transmission power is a network option, i.e., the operator may choose to apply it or not, in one direction or in both. All mobile stations, though must support the feature, thereby allowing power control to be efficient when utilized [42].

In our model, we have simulated transmitter power control for Class 5 mobile stations. In other words, the transmitter power of every user is asynchronously changed in 2 dB steps. With the aid of the soft dropping technique, the system calculates the target SIR based on the current transmitter power and subsequently the new transmitter power from (2.7) for every terminal asynchronously after every 480 ms. However, a valid transmitter power assignment is then evaluated in 2 dB steps such that the difference between the calculated power, from the iteration (2.7), and the assignment is less than 1 dB. Thus unlike the GSM system, where the mobile can raise its power periodically until the next SACCH message, the simulation model performs power control such that the mobile adjusts its transmitter power in a single step every 480 ms.

4.3.4 Handover management in GSM

In the GSM system, measurements of the received signal strength , the signal quality, and the mobile to base station distance have been proposed to serve as a basis for correct handover decisions [43]. Compared to previous cellular system where measurements are only made by the base stations, it is an important improvement in the GSM system that the mobiles as well measure signal strength and signal quality and report the obtained values in short intervals to their corresponding base station. This feature is part of the GSM recommendations and therefore a mandatory standard. No concrete handover has been standardized for the GSM system, though an example for an algorithm is given in the standards which demonstrates the usage of all the parameters defined. Due to improved algorithms which realize a hysteresis and which use several threshold values, handover procedures based on signal strength measurements can show a rather good behavior [27].

The handover procedure we have employed for simulation is signal strength based and is described as follows. If the terminal finds that the received signal strength index (RSSI) or path gain (negative path loss) of a neighboring base station is h higher than the one the user is presently connected to, it will attempt an intercell handoff to that base station. An intercell handoff attempt fails if the base station is unable to find an unoccupied channel or it does not have sufficient power to achieve the upper limit on target SIR constraint for soft drop, $\overline{\Gamma}_j$, on the minimum interference channel it had been assigned. The call is dropped if,

- the SIR achieved after it performs the handoff to the new base station is below the SIR threshold, or,
- the mobile user fails to do a handoff within the allowable outage duration, T_{out}, when the SIR falls below the threshold, Γ_{drop}.

Since the MS periodically reports signal quality measurements for links to neighboring base stations, we will employ this technique for simulation of handovers in the system.

4.4 Results and analysis

In this section we will discuss and analyze the results obtained from simulations of soft dropping power control strategy as part of an integrated radio resource management technique in an environment that attempts to incorporate the relevant radio resource allocation methods of a GSM system. In the previous section we discussed the validity of the base station assignment scheme, the admission control, and the RSSI based handover management scheme that we have simulated.

With an aim to study the impact of the RSSI hysteresis h and the two sets of soft dropping parameters, *viz.*, uplink transmitter power constraints and the range of uplink target SIRs, we will also compare the performance of the system under the influence of these constraints with that of fixed target SIR algorithm. This will enable us to not only understand the effect of the inherent soft dropping parameters and the pertinent handover strategy but also the improvement in performance over the fixed target power control. Thus the ensuing sections will throw more light on the following cases of implementation,

- change in the RSSI hysteresis h: h = 0, 6, 9 or 12 dB with soft dropping power control being performed with $\hat{q}_j$ = -1 dB, $\overline{q}_j$ = -17 dB, $\overline{\Gamma}_j$ = 9 dB, and $\hat{\Gamma}_j$ = 7 dB.

Notation	Parameter	Value
B	Number of Base Stations	20
h	Height of antenna	50 m
M	No. of channels in each cell	30
N	No. of neighbors each base station has	19
α	Propagation exponent	4.0
σ	Std. deviation of the shadow fading	6 dB
D	Shadow Fading correlation distance	50 m
δ	Resolution of distance on the system	20 m
N_0	Receiver Noise Power	-150 dBm
P_{max}	Maximum terminal transmitter power	0.8 Watts
P_{min}	Minimum terminal transmitter power	19.9 m-Watts
v_{min}	Minimum speed	60 km/hr
v_{max}	Maximum speed	120 km/hr
v_{mean}	Mean speed	90 km/hr
T_{sim}	Total simulation time	6000 sec
$T_{PosUpdat}$	Time between position updates	0.2 sec
T_{stats}	Time between statistics collection	1 sec
$T_{RsrcMgt}$	Time between resource management events	0.5 sec
$T_{PwrCtrl}$	Time between each power control iteration	0.48 sec
T_{out}	Outage duration	5 sec
Γ_{new}	SIR requirement for admission	10 dB
Γ_d	SIR threshold for quality transmission	6 dB

Table 4.1: Simulation parameters for a two dimensional macro-cell environment for a GSM-type system

- change in the soft drop power threshold, $\overline{q}_j$: $\overline{q}_j$ = -5, -11 or -17 dB with $\hat{q}_j$ = -1 dB, $\overline{\Gamma}_j$ = 9 dB, and $\hat{\Gamma}_j$ = 7 dB. The handover is performed with zero hysteresis.

- change in the range of uplink target SIRs: Table 4.2 shows the values specified for target SIR constraints. We will fix the uplink transmitter power constraints to $\overline{q}_j$ = -17 dB and $\hat{q}_j$ = -1 dB.

Comparison results are also shown with fixed target SIR power control for 9 dB. The other SIR thresholds are as shown in Table 4.1 and the results are investigated. Table 4.1 also contains the various parameters specified for the simulation environment as in [24]. The T_{sim} denotes the system time over which the entire simulation is run. The geographic positions of all the mobiles in the system is updated synchronously every $T_{PosUpdat}$ seconds depending on the mobiles velocity. Resource management and power control for each mobile are performed periodically and asynchronously every $T_{RsrcMgt}$ and $T_{PwrCtrl}$ seconds respectively. Calls are dropped when the signal quality of the radio connection is found to be below the threshold requirement, Γ_d, for longer than the outage duration, T_{out} seconds.

4.4.1 Impact of change in RSSI hysteresis, h, on system performance

Handoffs in this scheme are performed on the basis of the path gain and are independent of the interference and the load (traffic) in the system. Consistent with [24], it is found that a small RSSI hysteresis h leads to more handoffs back and forth (ping-pong effect) between the two adjacent bases on either side of the boundary. However large hysteresis delays the handover until the mobile is relatively closer to the new base. Consequently there is a reduction in the average number of handovers that the mobiles would attempt for and a rise in the average distance at which the handover is performed, from the old base. It was also found (Figure 4.4) that with large hysteresis, the mobiles tend to burn relatively higher battery power compared to mobiles that were performing handovers with lower RSSI hysteresis. We can attribute such a behavior to the fact that mobiles using larger hysteresis tend to keep transmitting relatively higher power for a longer time

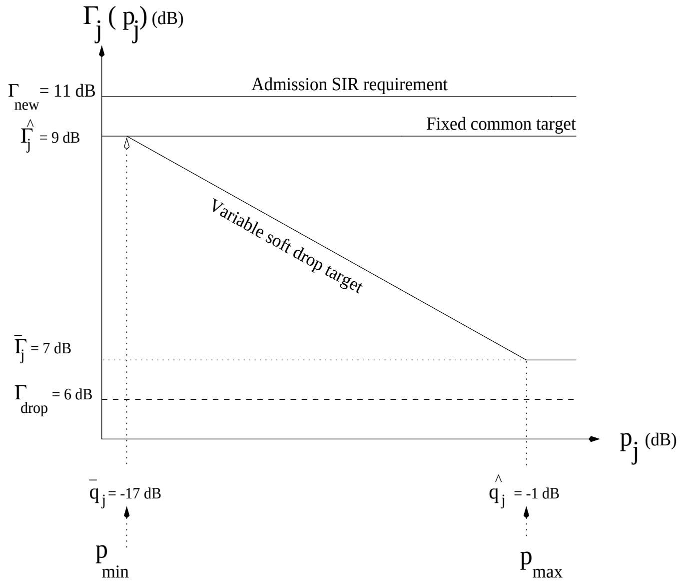
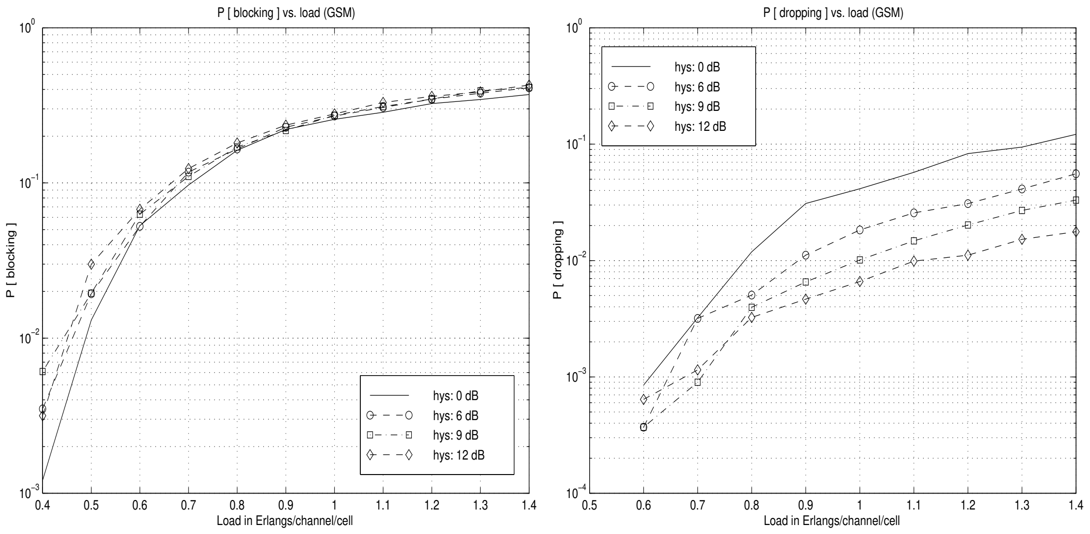
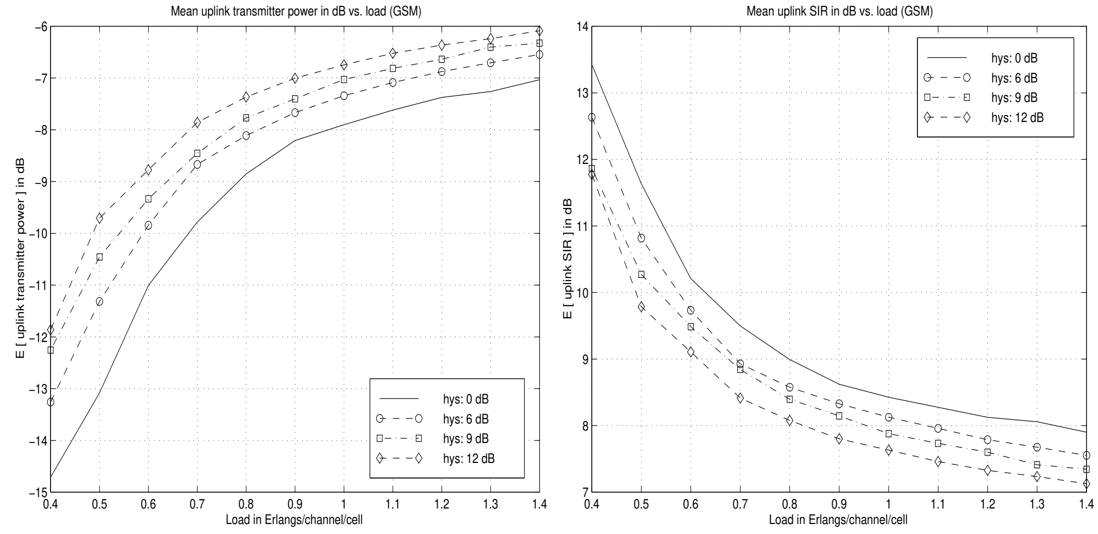


Figure 4.2: Soft dropping with varying hysteresis h = 0, 6, 9, 12 dB.



(a) (b)

Figure 4.3: (a) Blocking and (b) dropping performance of GSM-type system for different instances of RSSI hysteresis h= 0, 6, 9, 12 dB



(a) (b)

Figure 4.4: (a) Average uplink transmitter power and (b) average uplink SIR observed over the whole period of simulation for different instances of RSSI hysteresis h= 0, 6, 9, 12 dB

in order to satisfy the minimum quality requirements. Due to the delay in performing the handover and the proximity of the mobiles to the new base, we also observe a high probability in performing a successful handover. Thus Figure 4.3 shows that the call dropping is reduced with large hysteresis. We also observe small deterioration in the blocking performance with an increase in the hysteresis due to the raised power and consequent interference levels. The mean number of attempts for handovers are insensitive to changes in the traffic, due to the dependence of the handover strategy on path gain.

4.4.2 Impact of change in the soft drop power threshold, $\overline{q}_j$, on system performance

In this section we will discuss the impact of change in the soft drop power threshold, $\overline{q}_j$, on the overall performance of the system and also the improvement when compared to a fixed target strategy. All the results for this section have been performed with RSSI hysteresis $h = 0$ dB. In the simulations under discussion, the upper limit on transmitter

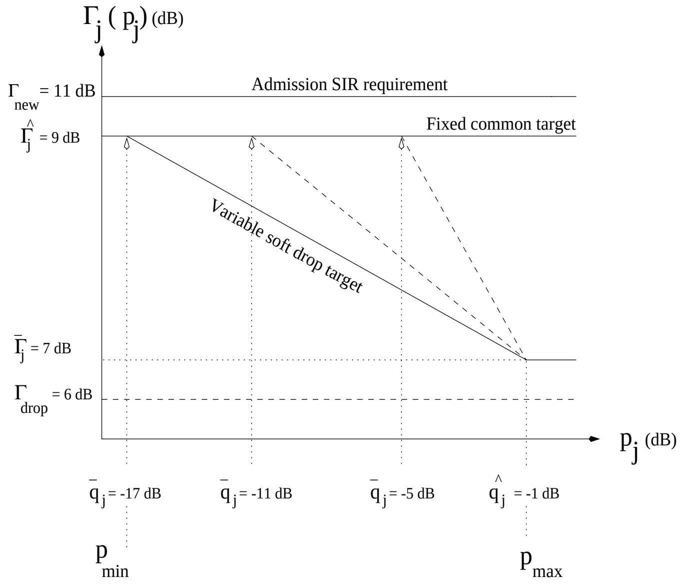
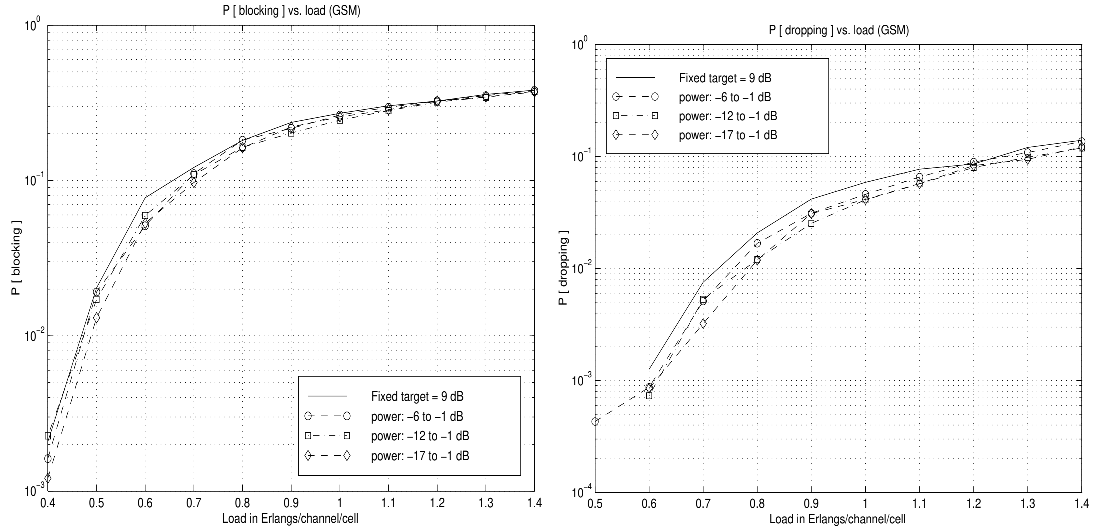


Figure 4.5: Soft dropping with varying $\overline{q}_j$

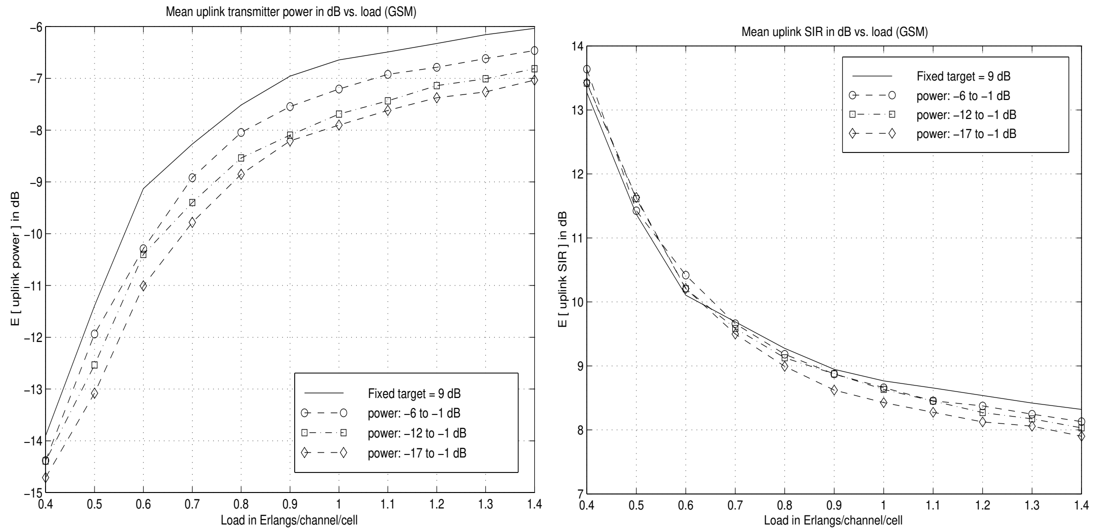
power for soft drop, $\hat{q}_j$, has been specified as -1 dB (Figure 4.5), which is also the maximum transmitter power for the Class 5 mobile stations in GSM system. Since the focus here is on the infeasible power control problem that occurs when the mobiles have reached the maximum power constraint and have been unable to achieve the target SIR, we will present three different instances of the soft drop power threshold, $\overline{q}_j$. The primary goal here is to investigate how the value of the soft drop power threshold influences the system performance. In simple words, how soon, in terms of the user's current transmitter power, should the user start aiming for a lower target SIR to avoid the negative implications on system performance caused by potential infeasibility of the power control problem. Radio transmission at relatively lower power when the mobile is close to the boundary, is also beneficial in the case of variable target SIR scheme due to fall in contribution to the co-channel interference observed at the neighboring base stations. This is unlike the case of fixed target scheme, in which the user attempts to boost the transmitter power in order to achieve the common target SIR, irrespective of its current transmitter power. The different instances under study are as shown in Figure 4.5.

Large range of uplink transmitter power constraints in soft dropping leads to constrained



(a) (b)

Figure 4.6: (a) Blocking and (b) dropping performance of GSM-type system for different instances of the lower limit of soft dropping power constraint, $\overline{q}_j$



(a) (b)

Figure 4.7: (a) Average uplink transmitter power and (b) average uplink SIR observed over the whole period of simulation for different instances of the lower limit of soft dropping power constraint, $\overline{q}_j$.

and beneficial target SIR control for a wider range of power steps. Thus lower the value of $\overline{q}_j$ (i.e., wider the soft drop region), higher is the possibility of the mobile aiming for a target SIR that is lower than the fixed target SIR (i.e., $\overline{\Gamma}_j = \Gamma_j = 9$ dB). All the mobiles outside the soft drop region ($< \overline{q}_j$) aim for a target SIR, $\Gamma_j(p_j) = \overline{\Gamma}_j = \Gamma_j$, which is also the same as the response of the mobiles operating under fixed target scheme. Thus irrespective of the current transmitter power the user always aims for the fixed target, Γ_j. Reducing the power threshold, $\overline{q}_j$, leads to a considerable reduction in the transmitter power levels in the system (Figure 4.4 (a)). However, we should not ignore the fact that reduced power levels also lead to a tolerable amount of deterioration in the signal quality level of the radio connection as observed in Figure 4.4 (b). The decrease in power levels can be attributed to the fact that fewer users will aim for the upper limit SIR, $\overline{\Gamma}_j$. Thus with soft dropping power control the subscribers' terminals tend to reduce the level of co-channel interference by a large amount. Also wider the range of soft drop transmitter power constraints (wider soft drop region), lower is the co-channel interference level in the system due to the variable target quality (SIRs). Another positive consequence of the reduction in interference level is the increase in the number of new calls that are admitted to the system and the decrease in the number of calls that are dropped close to the cell boundary. Figure 4.6 (a) exhibits modest improvement in the blocking performance of the system with soft dropping.

We should note the behavior of the mobiles employing variable target SIR algorithms that are attempting to perform handovers. The need for handovers is detected at the same time since the requirement for a handover is dependent solely on the signal strength. In the case of soft dropping, terminals close to the boundary of the cell will have low target SIRs because they will be transmitting at high powers to keep a good quality connection. These terminals will also be capable of achieving those above-the-threshold target SIRs and below the upper limit on target SIR, $\overline{\Gamma}_j$, due to the relatively low level of interference in the system. This is unlike the behavior of terminals operating under fixed target strategies. Under a fixed target SIR algorithm, the system will approach an infeasible power control state where the terminals will be aiming for a high common and unachievable target SIR with maximum transmitter power. Due to such behavior, the terminals will not only increase the interference level but will also fail to achieve the target SIR. Some terminals might even fail to achieve the minimum quality requirements and get dropped. In Figure 4.7 we observe notable improvement in power levels only at high traffic loads (approx. 0.6 Erlangs/channel/cell), which is also the load at which call dropping becomes significant. In this case, soft dropping helps in bringing about the reduction in the total interference at the base on a particular channel by keeping the link quality objective $\Gamma_j(p_j) \leq \overline{\Gamma}_j = \Gamma_j$.

4.4.3 Impact of change in the range of target SIR constraints, $\hat{\Gamma}_j$ to $\overline{\Gamma}_j$, on system performance

In the previous section we studied how significantly the set of transmitter power constraints could influence the performance of the system. In this section we will discuss the impact of changing the range of soft drop target SIRs (Table 4.2 and Figure 4.8). The four instances under discussion are as shown in Figure 4.8. The transmitter power constraints are kept fixed at $\overline{q}_j$ = -17 dB and $\hat{q}_j$ = -1 dB. Fixed target power control is performed at 9 dB.

Case I clearly stands out with the best overall performance in terms of the calls blocked (Figure 4.9(a))and dropped (Figure 4.9(b)), the transmitter power levels (Figure 4.10(a)) and the quality of the connection (Figure 4.10(b)). The range of target SIRs in Case II is higher than that of the first case. Thus in a situation of infeasibility of power control problem the terminals tend to aim for higher target SIRs and raise the level of co-channel interference in the system. The consequence is that the number of calls blocked at origination and number of calls dropped or forcefully terminated is

Soft drop/Fixed target	Transmitter power limits		Target SIR limits		Case
	$\overline{q}_j$ (dB)	$\hat{q}_j$ (dB)	$\hat{\Gamma}_j$ (dB)	$\overline{\Gamma}_j$ (dB)	
Soft drop	-17	-1	7	9	I
			8	10	II
			8	9	III
Fixed target	-17	-1	Γ_j = 9 dB		IV

Table 4.2: Varying limits for target SIR constraints for soft dropping

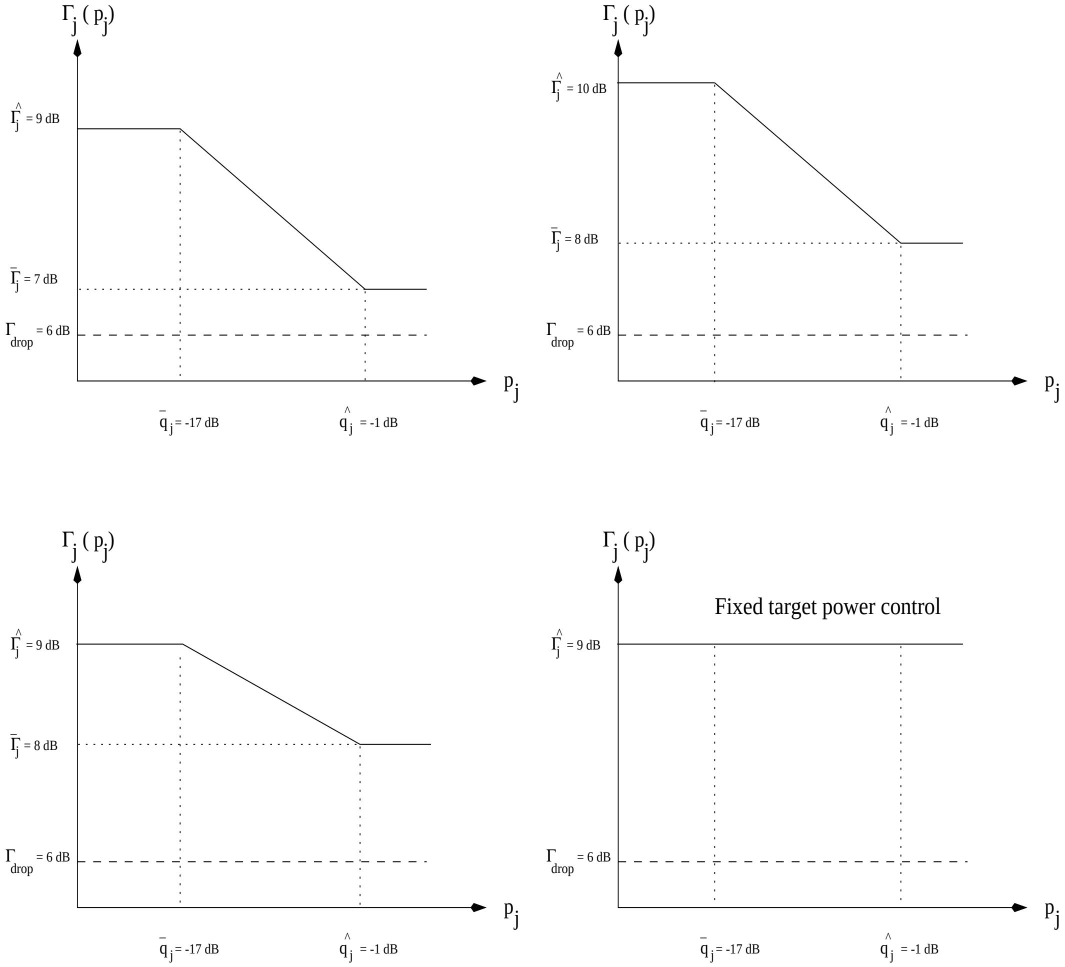
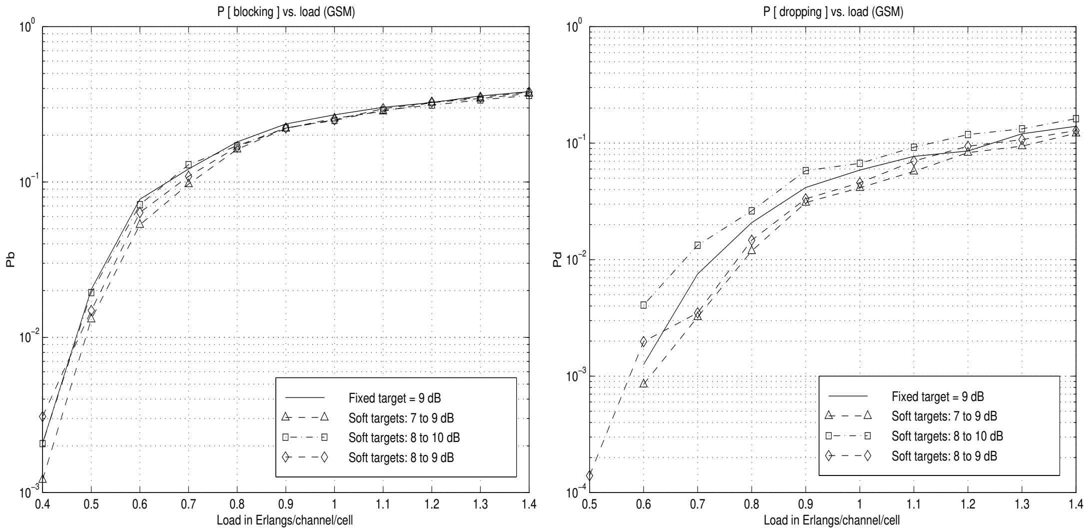
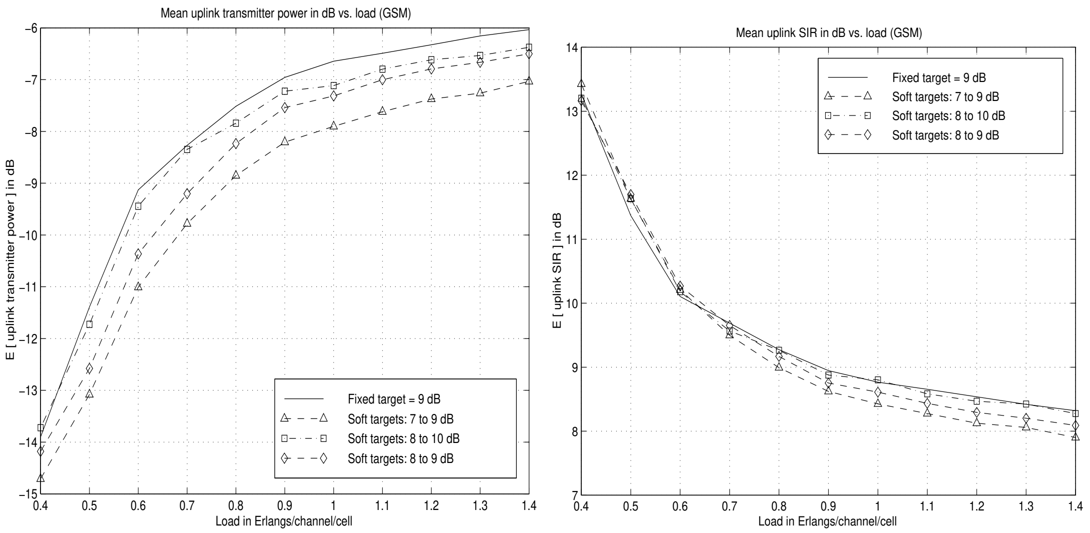


Figure 4.8: Soft dropping with different instances of range of uplink target SIR constraints



(a) (b)

Figure 4.9: (a)Blocking and (b) dropping performance for varying range of uplink target SIR constraints, $\hat{\Gamma}_j$ and $\overline{\Gamma}_j$, with h= 0 dB.



(a) (b)

Figure 4.10: (a) Average uplink transmitter power and (b) average uplink SIR observed over the whole period of simulation for varying range of target SIR constraints, $\hat{\Gamma}_j$ to $\overline{\Gamma}_j$ with h= 0 dB

higher than the instance of even fixed target power control. We can therefore conclude that it is advisable to typically specify the the upper limit on soft drop target SIR, $\overline{\Gamma}_j = \Gamma_j$. In the third instance, we have specified the the upper limit on target SIR to be equal to the value specified for fixed target ($\overline{\Gamma}_j = \Gamma_j = 9$ dB), however we reduced the range of target SIRs by raising the lower limit for the terminals' target SIRs to $\hat{\Gamma}_j =$ 8 dB. The performance of the system under such constraints is better than the second instance, but is obviously worse when compared to the first instance. The exposition is the relatively higher possibility of the terminals aiming for high target SIRs when approaching an infeasible power control problem in the third case. However, we should not fail to notice the betterment of soft dropping over fixed target in the first and the third instances.

4.5 Conclusions

The region of soft dropping power control operation is primarily decided by two sets of limits (Section 3.6). Results in this chapter clearly displayed the importance of soft dropping power threshold, $\overline{q}_j$, with specified values for the upper limit, $\hat{q}_j$, on transmitter power and the set of target SIR constraints ($\hat{\Gamma}_j$ and $\overline{\Gamma}_j$); all being collectively responsible for definition of the soft drop region. The lower the value of the power threshold, the wider is the soft drop region and therefore the users start aiming for lower target SIRs relatively earlier (compared to users that will have smaller soft drop region or large values of the power threshold, $\overline{q}_j$). Thus the reduction in battery power consumption with lower power thresholds is considerable as observed in the results. Results for the mean signal quality in the simulations showed that this reduction in battery power did not come at the cost of signal quality. The deterioration in signal quality is relatively modest and hence the overall performance of the system is favorable. The increase in the number of users supported by the system was also evident in the results. With fixed transmitter power constraints on the user, $\overline{q}_j$ and $\hat{q}_j$, varying range of the target SIRs also gave us an insight into importance of the limits and how the decision of these values could nullify the improvement in the performance. Simulation of step change in user's transmitter power level as part of the power control constraint on the mobile however prevented us from studying the impact of averaging factor β on the performance. We will investigate its influence in Chapter 5. We have seen that soft dropping can provide noticeable performance improvements even in a GSM environment where the power control is relatively slow and coarse at the cost of increasing the complexity of the power control at the base by a small amount. The general approach of soft dropping can be applied to almost any power controlled system. We expect that in other environments, notably IS-95, the improvements may be even more dramatic.

Chapter 5

Soft dropping for CDMA system

Spread spectrum technology has been used in military communications for over half a century to overcome the effects of strong intentional interference (jamming), and to hide the signal from the eavesdropper (covertness). Recently spread spectrum based code division multiple access (CDMA) was proposed to support simultaneous communication among a large community of relatively uncoordinated users. This proposal stimulated theoretical work which revealed some of the strengths and weaknesses of spread spectrum in cellular applications. Work in [37] recognized that since CDMA capacity is primarily interference limited, any reduction in the interference converts directly and linearly into an increase in capacity. While it is similar in implementation to its military predecessors, the spread spectrum wireless network achieves efficiency improvements by incorporating a number of unique features made possible by benign noise-like characteristics of the interfering signal waveforms.

In this chapter we will investigate and evaluate the application of soft dropping to a CDMA type system. The basic cellular radio network employed in our evaluation is similar to that used for the GSM model except for the radio resource management schemes that will be described in this chapter. The first half of the chapter covers a brief overview of the IS-95 CDMA system and a discussion of the parallels between the CDMA standard and model employed for simulation purposes. The differences between the models employed for simulation of GSM-type and CDMA-type system are also briefly summarized in Table 5.1. The second half of the chapter will bring to focus the simulation results that display remarkable improvements in the system performance. The cell layout (Section 3.1), call traffic parameters (Section 3.2), mobility model (Section 3.3) and the propagation models (Section 3.4) remain the same as given in Chapter 3.

5.1 Network Architecture of the IS-95

Relative to earlier systems, one of the many innovations of the IS-95 system is the introduction of the "soft handoff" mechanism [35], in which a terminal establishes contact with a new base before giving up its radio link to the original base. Thus the transition is from the original cell to both the cells and then to the new cell. That is, the analog system (and the digital TDMA-based systems) provide a break-before-make switching function whereas the CDMA-based handoff system provides a make-before-break switching function. Not only does this minimize the probability of dropping, but it also makes the handoff virtually undetectable by the user.

When a call is in the soft handoff condition, two or more base stations simultaneously listen for the coded speech signals transmitted by a terminal. Both base stations send their demodulated signals to the switch (MTSO) which estimates the quality of the two signals and sends one of them to a speech decoder. A complementary process takes place in the forward direction. The switch sends coded speech signals to both base stations which transmit them simultaneously to the terminal. The terminal combines the signals received from the two base stations and demodulates the result. Thus we have the network architecture illustrated in Figure 5.1, which shows the vocoders in the switch rather than in the base stations.

CDMA soft handoff requires base stations to operate in synchronism with one another. All base station digital transmissions are referenced to a common CDMA system-wide time scale that uses the Global Positioning System (GPS) time scale [35]. In order to achieve the necessary synchronization, all base stations contain GPS receivers. A network of GPS satellites transmits signals that include precise time information, accurate to within one microsecond, relative to Universal coordinated Time, an international standard

Simulations	TDMA/FDMA system	CDMA system
Channels/cell	Multiple	Single
Radio transmissions	Single user/channel/base	Multiple users/channel/base
Base assignment	Strongest pilot strength	Minimum power transmission
Admission control	Minimum SIR requirement	Minimum SIR requirement
Channel allocation	Minimum interference	Not applicable
Handoff/handover	RSSI with hysteresis	Minimum power based with Timer

Table 5.1: Difference between simulations performed for TDMA/FDMA- and CDMA-based systems

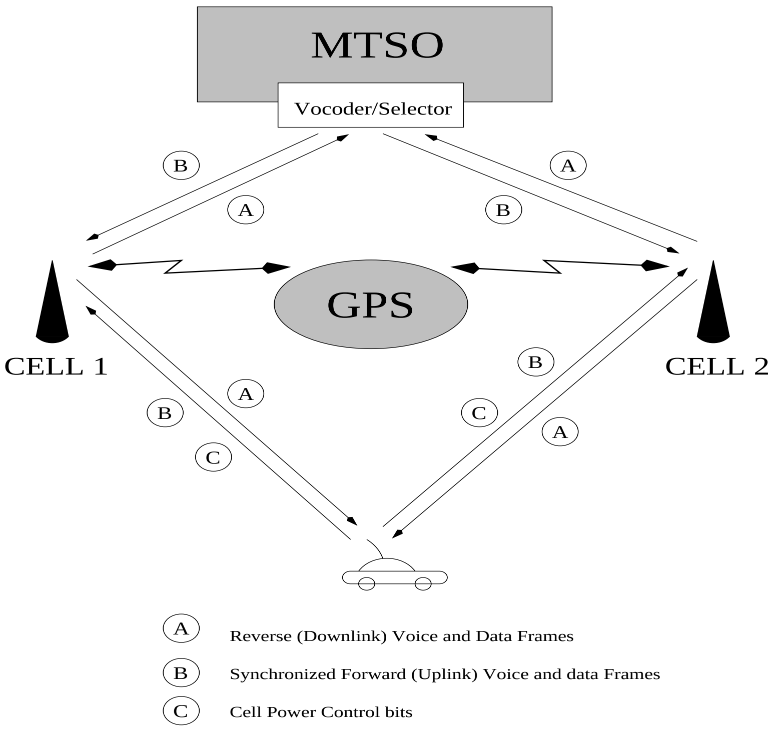


Figure 5.1: CDMA Architecture depicting a soft handoff situation. The diagram shows two active links during handoff. One is the original cell and the second is the desired new cell identified by the subscriber.

5.2 Radio transmission

CDMA radio transmission differs significantly from the techniques employed in the other systems. Four important differences as described in [21], can be briefly summarized here as follows:

- IS-95 employs different transmission techniques in the uplink and downlink directions. In the other systems, forward and reverse transmissions are identical or very similar.
- There are two stages of baseband modulation in an IS-95 system, compared with one in other systems.
- To maximize spectrum efficiency, the IS-95 system employs variable bit-rate traffic channels. The other systems have constant-bit-rate-channels.
- The IS-95 system has a reuse factor of one. Each radio channel is used in all sectors of all cells.

The simulations performed for a CDMA system in this work however ignore the modulation process and it has been assumed that every base receives the subscribers signals error- and delay-free. There is assumed to be no difference between the uplink and downlink radio channel characteristics.

5.3 Radio Resource Management

In this section we will briefly discuss the access technique used for a new call (Section 5.3.1), admission of the caller to the system (Section 5.3.2), transmitter power control (Section 5.3.3) and soft handoff management technique (Section 5.3.4) employed in CDMA operation of IS-95 and the simulation model.

5.3.1 System pilot acquisition

In the IS-95 cellular telephone system, each cell site transmits a pilot carrier signal. This pilot carrier is used by the mobile station to provide robust time, frequency, and phase tracking of the signals from the cell site. The admission of the new caller to the system is by repeated but limited number of attempts to be "heard" or received accurately by the parent base in the presence of interference. The new call always attempts to connect to the base with the highest gain.

The base station assignment scheme under consideration in this model is similar to that employed for the GSM-type system in Section 4.3.1.

5.3.2 Admission Control

In the present U. S. cellular environment, the FCC has allocated 25 MHz of spectrum which is equally split between two system operators in each service area. For a fixed channel allocation strategy, the spectrum is further divided between the cells, with a maximum of 57 analog FM channels in a three sector cell site. When demand for service is at a peak, the 58th caller in a given cell must be given a busy signal. There is no way to add even one more caller to a fully occupied system. With the CDMA system, however, there is a much softer relationship between the number of users and the grade of service. For example, the system operator could decide to allow a small degradation in the bit error rate and increase the number of available channels during peak hours.

This capability is especially important for avoiding dropped calls at handoff because of a lack of channels. In the analog system and in digital TDMA, if a channel is not available, the call must be reassigned to a second candidate or it will be dropped at the handoff. With CDMA, however, the call must be accommodated if it is acceptable to slightly deteriorate the users' signal quality until another call is completed. In our simulations for a CDMA system we have attempted to imitate a similar call admission behavior dependent on the signal quality achievable by the service-seeking user. Thus every new caller that attempts to connect to the strongest pilot signal base is admitted only if the user can achieve the SIR threshold, Γ_{new}, fixed for all new calls. The only difference with the admission control scheme for GSM system (Section 4.3.2), is that the number of channels at a base station's disposal is only one and more than one user can be supported on a single frequency band available at a base station.

5.3.3 Power control

To achieve high capacity, quality, and other benefits, the IS-95 mobile telephone system employs uplink and downlink power control. Theoretical studies [35, 36, 38] reveal that in order to achieve high capacity, a CDMA system has to maintain a narrow range of received power levels among the signals arriving at a base station. When there is a disparity in received powers, the strong signals interfere excessively with the weaker ones and unduly limit the total number of simultaneous transmissions consistent with a signal quality objective. In order to confine the received signal powers to a narrow range, IS-95 performs a combination of "open loop" and "closed loop" operations to control the power of the transmitters at the moble terminals.

The uplink open loop power control is primarily a function of the mobile user. The goal for each user is to estimate the path loss from the base to the mobile. The open loop power control mechanism, which is analog in nature and has about 85 dB or more dynamic range, provides for a very rapid response over a period of just a few microseconds.

Generally, however, this is not effective enough: the uplink and the downlink channel characteristics are asymmetric, particularly when the frequency separation (45 MHz) between them is large. To overcome this disparity in path loss, when the base determines that any user's received signal on the reverse link has too high or too low a power level (or more precisely SIR level), a one bit command is sent by the base to the user, at a rate of once every 1.25 ms, over the downlink to lower or raise its relative power by a fixed amount, $\Delta = 0.5$ dB. This mechanism is called closed loop power control;

consisting of the inner loop and the outer loop. The outer loop[1] decides on a target SIR at the end of each frame (20 ms) and the inner loop provides for the base station to control the power of the mobile with the aid of messages every 1.25 ms.

The primary purpose for downlink power is to reduce power for units that are either stationary, relatively close to the base, impacted little by multipath fading and shadowing effects, or experiencing minimal other cell interference. Thus, extra power can be given to the users that are either in a more difficult environment or far away from the cell and experiencing high error rates.

Transmitter power control in this work is simulated for a Class III type of Mobile Station with an effective radiated power (ERP) from a half wave dipole not exceeding 1 W at maximum output. We will however discuss results for the uplink power control iteration[2] obtained by the application of the power control iteration in (2.7). Due to computational restrictions, power control iterations in the simulations are performed at the rate of 100 iterations per second instead of 800 iterations every second. However, the simulation model will perform these iterations with arbitrary changes in power level instead of discrete 1 dB power level changes in the real system.

5.3.4 Handoff management

After a call is initiated, the mobile continues to scan the neighboring cells to determine if the signal from another cell becomes comparable to that original cell. When this happens, it indicates to the base that the call has entered a new cell's coverage area and that a handoff can be initiated. The mobile transmits a control message to the MTSO which identifies the new base station and states the need for a handoff. The MTSO initiates the handoff by establishing a link to the mobile through the new cell while maintaining the old link. While the mobile is located in the transition region between the two base stations, the call is supported by communication through both

[1]Resides in the MTSO

[2]It is typically accepted that the uplink is the one that impacts the overall performance of the system

cells; thereby eliminating the ping ponging effect, or repeated requests to hand the call back and forth between the two base stations. The original base will only discontinue handling the call when the mobile is firmly established in the new cell. The paramount goal of the system is to make the mobile transmit at minimum power enough to keep the connection active or achieve the signal quality requirements.

The handoff algorithm - minimum power handoff (MPH), that we have employed in our simulations is also a transmitter power based scheme in which the mobiles constantly search for a base that minimizes the uplink transmitted power [23]. To avoid a "ping-pong" effect, a timer is introduced to delay the handoff. The algorithm can be described as follows.

A mobile j assigned to a base station a_j will run the MPH algorithm periodically to look for the base station k^*, that allows the upper limit on target SIR constraint for soft drop, $\overline{\Gamma}_j$, to be achieved with the minimum power. Thus the base k^* that requires minimum power for transmission from terminal j is

$$k^* = \arg\min_k \overline{\Gamma}_j \frac{I_{kj}}{h_{kj}} \tag{5.1}$$

Only if the best base k^* is not the current base a_j, a handoff attempt is made. To reduce the number of unnecessary handoffs, a conditional timer (T_{MPH}) is introduced to delay the handoff requests. Whenever the best base station differs from the current one, $k^* \neq a_j$, the maximum SIR that can be achieved at the current base station is estimated as

$$\Gamma_{\max} = p_{\max} h_{kj} / I_{kj} \tag{5.2}$$

It should be noted that $\Gamma_{\max}$ is only an optimistic estimate of the maximum achievable SIR since it neglects the response of other mobiles to maximum power transmission. If $\Gamma_{\max}$ is less than the minimum required SIR, Γ_d, the timer will not be invoked and handoff is allowed to take place due to the immediate need, only if the other rules are satisfied. Otherwise the timer is set. The timer will be incremented each time the condition $k^* \neq k_0$ is true. The handoffs are delayed until the timer reaches a specific count, T_{MPH}. When this happens the call will attempt to perform a handoff to the appropriate base station. The timer is then reset after the handoff succeeds. However, if the user's timer is less than the T_{MPH}, no handoffs will be made and the particular call will still be carried by the old base station with the power being adjusted accordingly. If the attempt for a handoff fails, the call is terminated when the user's signal quality (SIR) falls below the threshold, Γ_d, for longer than the outage duration.

5.4 Results and Analysis

Unlike a TDMA system where the interference observed by a user on its channel is only due to users transmitting on the same channel in neighboring cells, in the CDMA system under simulation, a user in a particular cell will observe interference from all the users in the system. Thus the pernicious effects of an infeasible power control problem (on a channel) on the system performance in a CDMA system are far more damaging than in a TDMA system.

In this section we will examine the results for an assortment of soft dropping parameter constraints. The method of performing analysis follows that in Chapter 4, in terms of the soft dropping power control scheme implementation and is as described below:

- change in the soft drop power threshold, $\overline{q}_j$: $\overline{q}_j$ = -20, -40, or -60 dB, with fixed $\hat{q}_j$ = -3 dB (0.5 W), $\overline{\Gamma}_j$ = -13 dB, and $\hat{\Gamma}_j$ = -15 dB. Comparison results are also shown in Section 5.4.1 with fixed target SIR power control for -13 dB.

- change in the range of uplink target SIRs, $\hat{\Gamma}_j$ and $\overline{\Gamma}_j$: We will fix the uplink transmitter power constraints and the target SIR for the fixed target scheme as in Table 5.3. The results are described in (Section 5.4.2)

- change in the rate of convergence, β: $\beta = 0.1, 0.3, 0.5, 0.7$, or 0.9 for soft dropping power control with specified $\hat{q}_j$ = -3 dB, $\overline{q}_j$ = -60 dB, $\overline{\Gamma}_j$ = -13 dB, $\hat{\Gamma}_j$ = -15 dB and $1/(1+\beta) = 0.97$ (Section 5.4.3).

Notation	Parameter	Value
B	Number of Base Stations	20
h	Height of antenna	50 m
M	No. of channels in each cell	1
N	No. of neighbors each base station has	19
α	Propagation exponent	4.0
σ	Std. deviation of the shadow fading	6 dB
D	Shadow Fading correlation distance	50 m
δ	Resolution of distance on the system	20 m
N_0	Receiver Noise Power	-150 dBm
P_{max}	Maximum terminal transmitter power	0.5 Watts (-3 dB)
P_{min}	Minimum terminal transmitter power	10^{-8} Watts (-80 dB)
v_{min}	Minimum speed	60 km/hr
v_{max}	Maximum speed	120 km/hr
v_{mean}	Mean speed	90 km/hr
T_{sim}	Total simulation time	10000 sec
$T_{posupdat}$	Time between position updates	1 sec
T_{stats}	Time between statistics collection	1 sec
$T_{rsrcmgt}$	Time between Resource Management events	0.5 sec
$T_{pwrctrl}$	Time between each Power Control iteration	0.01 sec
T_{out}	Outage duration	5 sec
Γ_{new}	SIR requirement for admission	-10 dB
Γ_d	SIR threshold for quality transmission	-16 dB
T_{MPH}	Timer for MPH based scheme	5

Table 5.2: Simulation parameters for a two dimensional macro-cell environment for a CDMA-type system

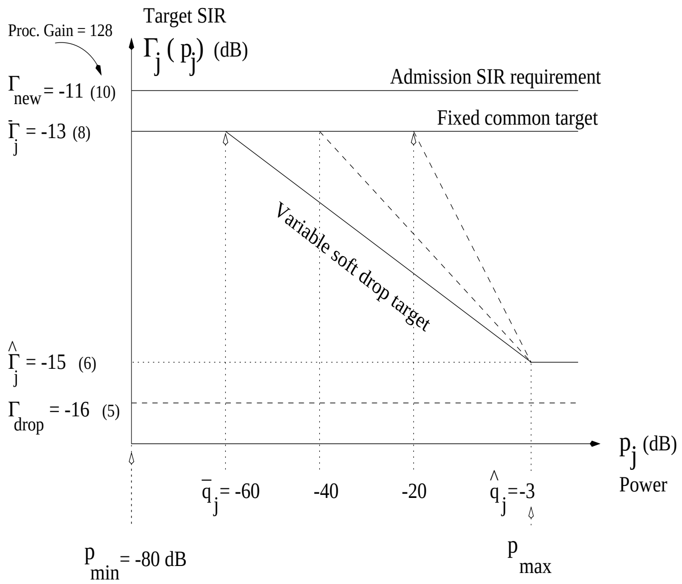
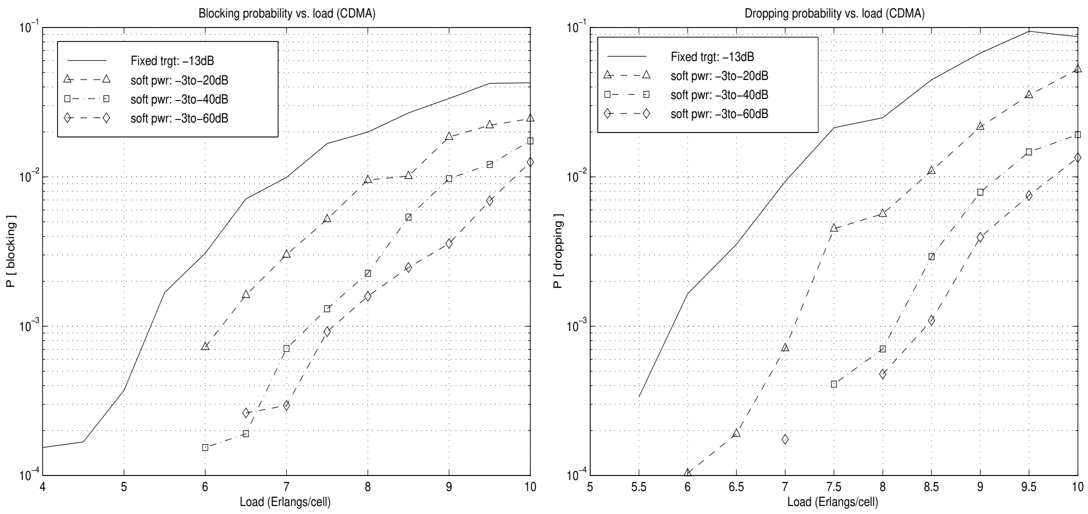


Figure 5.2: Soft dropping with varying $\overline{q}_j$



(a) (b)

Figure 5.3: (a) Blocking and (b) dropping performance of CDMA-type system for different instances of soft drop power threshold, $\overline{q}_j$, for soft dropping.

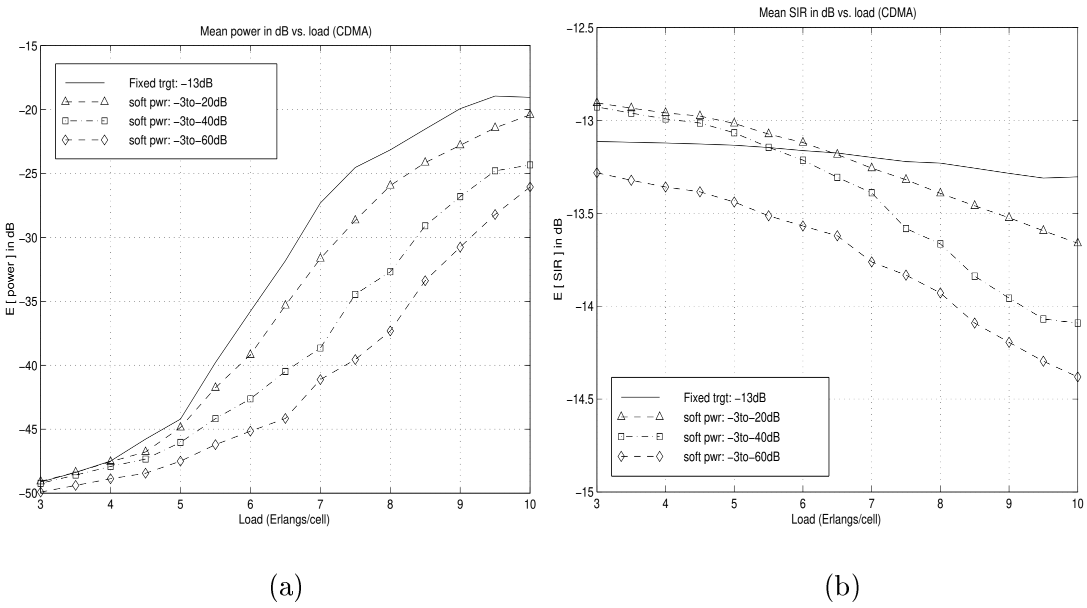


Figure 5.4: (a) Average uplink transmitter power and (b) SIR levels in dB observed over the whole period of simulation for different instances of soft drop power threshold, $\overline{q}_j$.

5.4.1 Impact of change in soft drop power threshold, $\overline{q}_j$, on system performance

In this section, similar to the analysis in Section 4.4.2, we will discuss the results obtained from simulations of varying soft drop power threshold[3], $\overline{q}_j$, for a single-channel/cell CDMA-type system. As observed in Figure 5.3 and Figure 5.4, with relevance to the user's transmitter power, the earlier the mobile is encouraged to aim for a low target SIR the lower is its contribution to level of interference in the neighboring cells and its own. Consequently the likelihood of supporting more users in the system rises, as is apparent in the simulation results. The calls that previously (as in the instance of fixed target) could not gain access to the system due to insufficient power to overcome the high interference and/or path loss will now be admitted to the system with a higher probability (Figure 5.3 (a)). Similarly calls that were dropped due to below-the-threshold signal quality, will now be able to maintain acceptable signal quality due to the huge reduction in interference level; see Figure 5.3 (b). The gain in

[3]Lower values correspond to wider soft drop region of power control operation

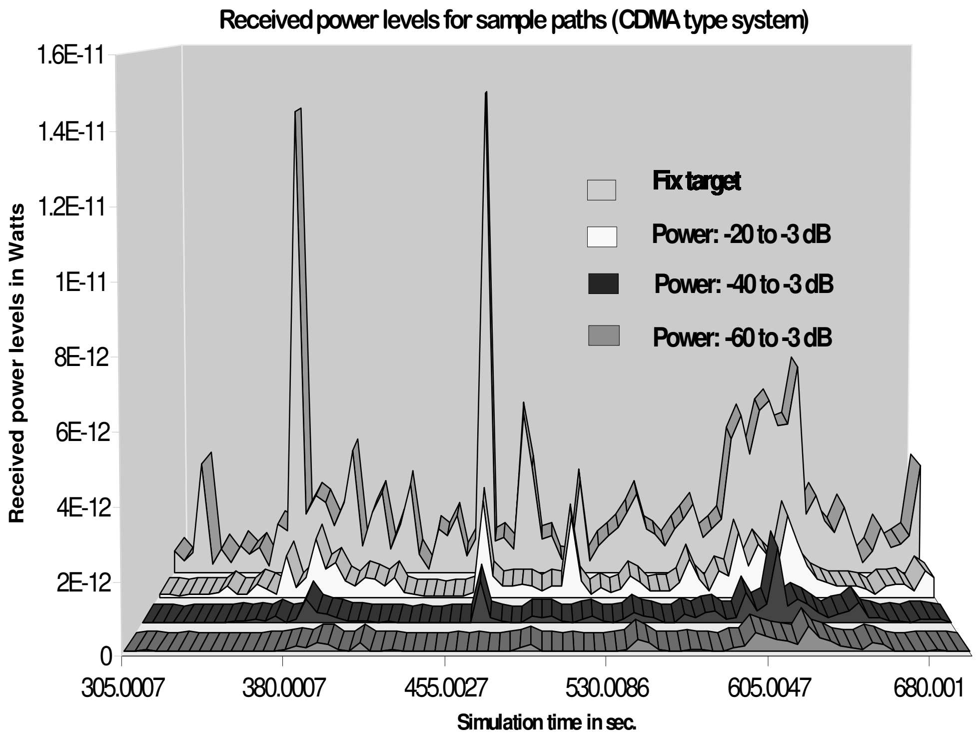


Figure 5.5: Received power levels in Watts at a base for random sample paths

Soft drop/Fixed target	Transmitter power limits		Target SIR limits		Case
	$\overline{q}_j$ (dB)	$\hat{q}_j$ (dB)	$\overline{\Gamma}_j$ (dB)	$\hat{\Gamma}_j$ (dB)	
+ Soft drop	-60	-3	-13	-15	I
			-12	-14	II
			-13	-14	III
Fixed target	-80	-3	Γ_j = -13 dB		IV

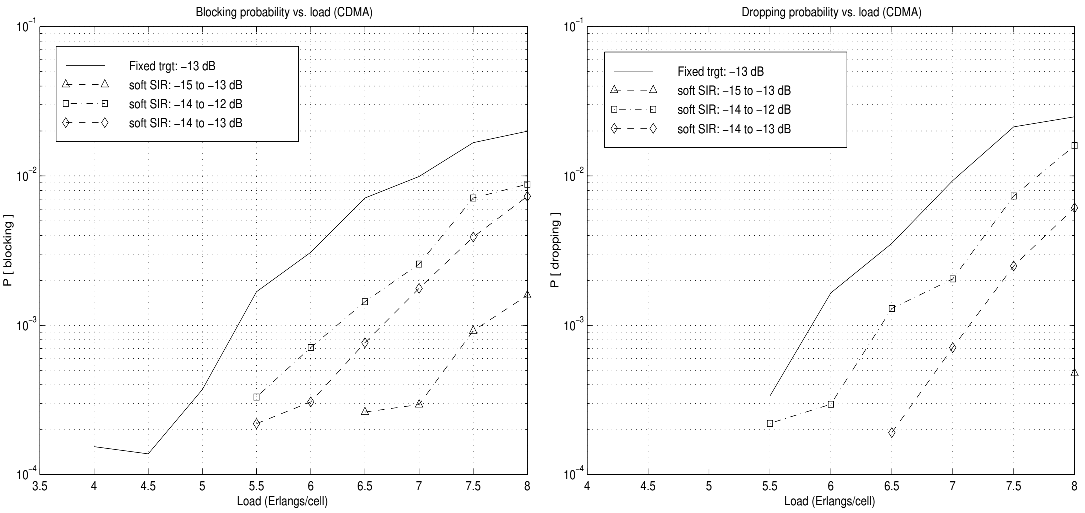
Table 5.3: Varying target SIR constraints, $\hat{\Gamma}_j$ to $\overline{\Gamma}_j$, for soft dropping in a CDMA environment

capacity is supplemented by the vast reduction in the average uplink transmitter power (Figure 5.4 (a)). This increase in system capacity and the fall in the average battery power compared to a system employing fixed target SIR are however not at the cost of unbearable damage to the signal quality. The deterioration in call quality (Figure 5.4 (b)) is sustainable and the gains in system performance not nullified. In fact, when the network is lightly loaded, the signal quality of the radio connection for narrow range of soft dropping transmitter power constraints is superior to that observed in common target scheme. This improvement is in addition to the fall in average power levels.

5.4.2 Impact of change in target SIR constraint, $\hat{\Gamma}_j$ to $\overline{\Gamma}_j$, on system performance

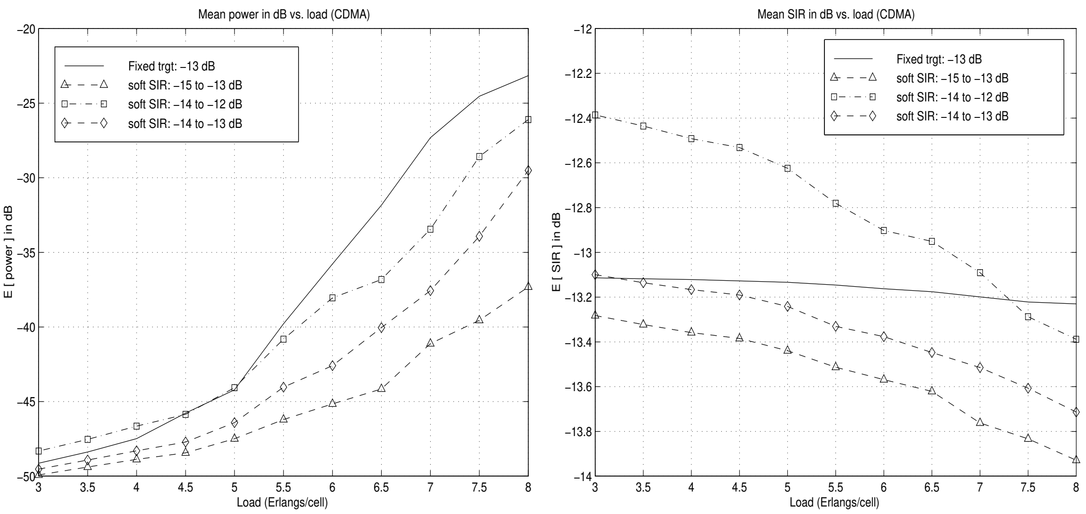
In this section we will discuss the impact of soft dropping target SIR constraints on the system performance. For the different cases under study in this section, refer to Table 5.3. Also, the averaging factor, β, is specified as 0.9. The results are similar to that observed for simulations of a TDMA system. Case I gives the best performance among the cases II through IV.

Firstly, let us investigate the behavior of the system for Cases I, II and IV. For Case IV, irrespective of the users' transmitter powers the target SIR remains fixed at $\Gamma_j =$ -13 dB. However for Cases I and II, under fixed range of transmitter power constraints, as long as the user has a transmitter power, $p_j \leq \hat{q}_j$, it will always aim for a target SIR, $\Gamma_j(p_j)$, that is relatively greater than that for Case I at a specified current transmitter power p_j. Though the target SIR in Case II is relatively higher compared to Case I



(a) (b)

Figure 5.6: (a) Blocking and (b) dropping performance of CDMA-type system for different instances of target SIR constraints for soft drop.



(a) (b)

Figure 5.7: (a) Average uplink transmitter power and (b) SIR levels in dB observed over the whole period of simulation for different instances of target SIR constraints for soft drop.

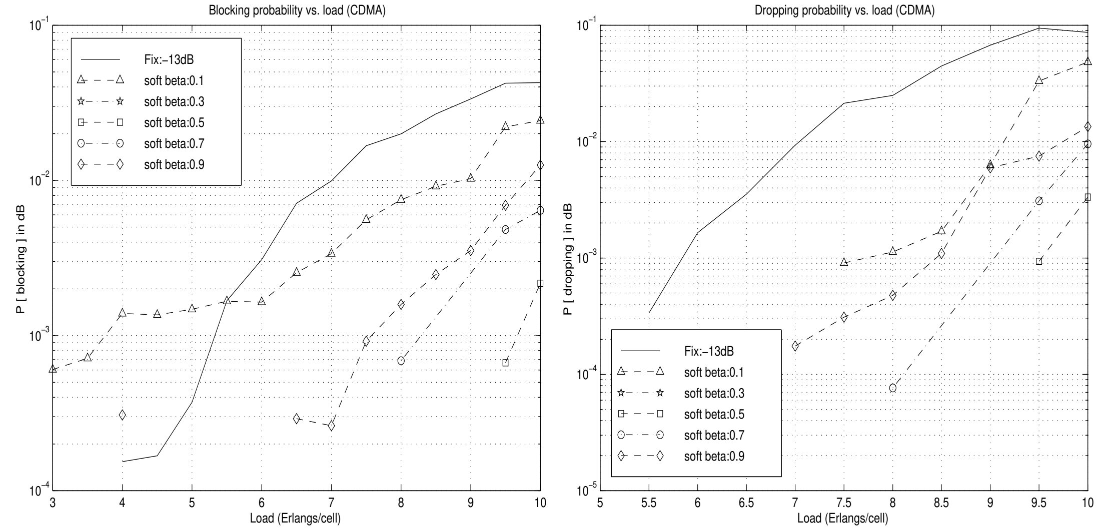
and IV, the system is able to provide improved connection as long as the system is lightly loaded (Figure 5.7 (b)). But if the user's current transmitter power is in the soft drop region, then the contribution to the total interference in the system will be comparatively higher due to a higher target SIR. Such a behavior is clearly observed in Figure 5.7 (a), where Case II has the highest average power level among all the soft dropping instances. We should not fail to notice the trade-off that exists between the improvement in signal quality and the overall reduction in battery power consumption. Also, the rise in interference levels due to high target SIRs, reduces the number of users supported by the network (Figure 5.6 (a) and (b)).

The second category of comparison involves Cases I, III and IV. For specified limits of soft dropping power constraints, the idea is to study the influence of a narrow range of target SIRs. With the reduction in the range of target SIRs from Case I to Case III, the users are encouraged to aim for higher target SIRs for a given transmitter power. Thus the deterioration in quality of connection is less compared to that in Case I (Figure 5.7 (b)). The consequence is that terminals also start consuming more battery power to achieve these relatively high target SIRs, as observed in Figure 5.7 (a). The reduction in the system capacity due to increased blocking and dropping with Case III is also a consequence of the increased interference in the system (Figure 5.6 (a) and (b)).

5.4.3 Impact of change in averaging factor, β, on system performance

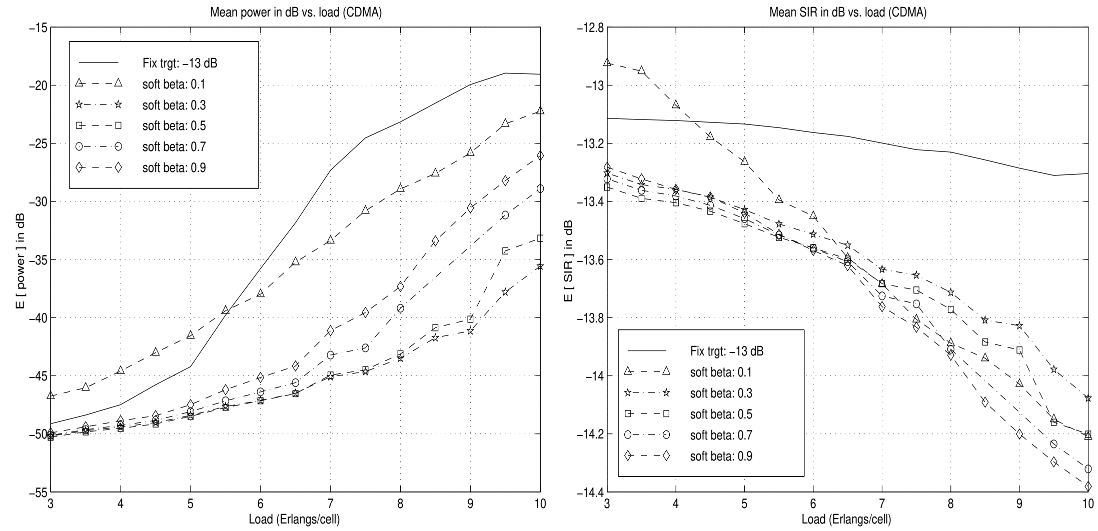
The effect of various values of β ($\beta_j = \beta \ \forall j$) on the overall performance is discussed in this section. We have employed a range of values of β, small to large, to study the nature of its influential behavior on the power control scheme, and system performance in general.

Every soft dropping power control iteration (2.7) of any user is a weighted average of the current power and the amount of power it needs to achieve the target SIR, $\Gamma_j(p_j)$, all in dB. The factor β_j is responsible for the averaging effect and helps prevent oscillatory behavior as observed in Figures 5.10 and 5.11 . In the sense that, for high values of β,



(a) (b)

Figure 5.8: (a) Blocking and (b) dropping performance of CDMA-type system for different instances of β for soft dropping.



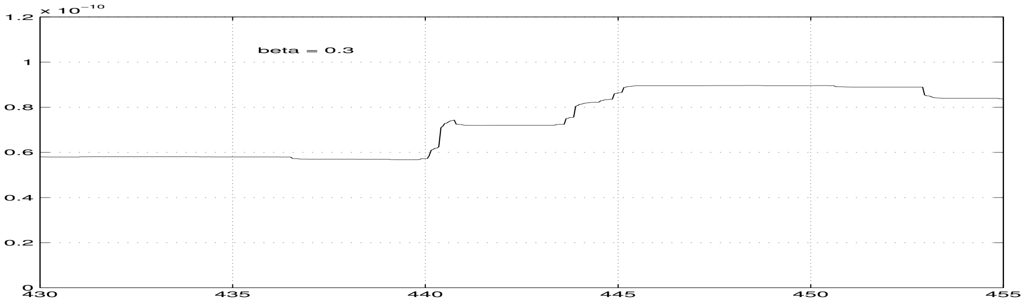
(a) (b)

Figure 5.9: (a) Average uplink transmitter power and (b) SIR levels in dB observed over the whole period of simulation for different instances of rate of convergence, β

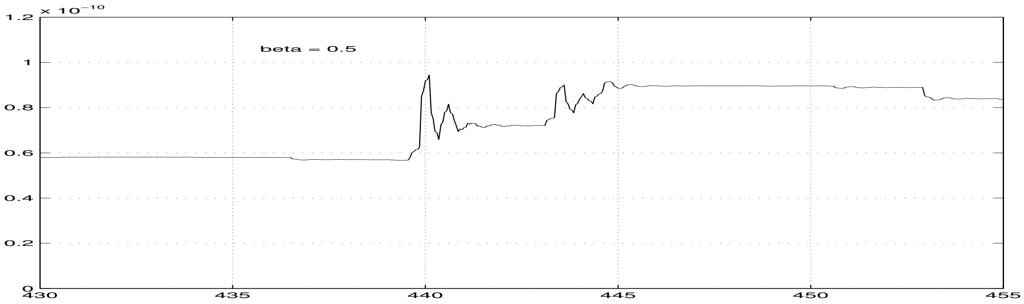
the user will aim for a low target SIR for high transmitter power and high target SIR for low transmitter power. The results in Figure 5.8 and 5.9 suggest a trivial increase in the interference levels at very high values of β. The result is, compared to users that employ intermediate values of β, the mean power level, dropping and blocking probabilities for users employing very high values of β will tend to be relatively higher, but much improved compared to systems employing common target schemes. However there is no significant deterioration in the quality of the connection compared to lower values of β.

Low values of β, are representative of slow convergence of the power control iteration due to insignificant power control action. That is, the user changes transmitter power very slowly to accomodate for the variable target SIR. Also, the user does not lower its power when it is close to the problem of infeasibility. The mean transmitter power levels of the active users thus remain relatively high compared to intermediate and high values of β, when a high initial power is assigned to the terminal at admission. At low traffic loads and low rate of convergence, β, the system is able to provide superior signal quality at the cost of high battery consumption.

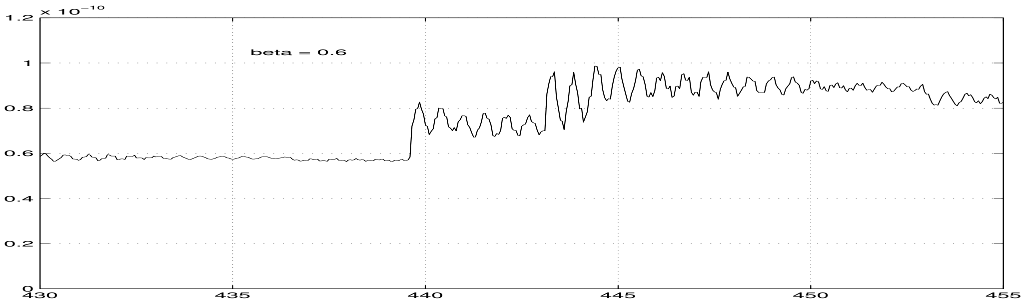
We can thus conclude that the system performance is robust to changes in the convergence factor, β, as long as it is not too low. The system performance in terms of battery power consumption and system capacity is improved remarkably with a trivial deterioration in the quality of connection. From previous results we can also conclude that the user can be provided with superior quality connection for the same amount of bettery power consumption.



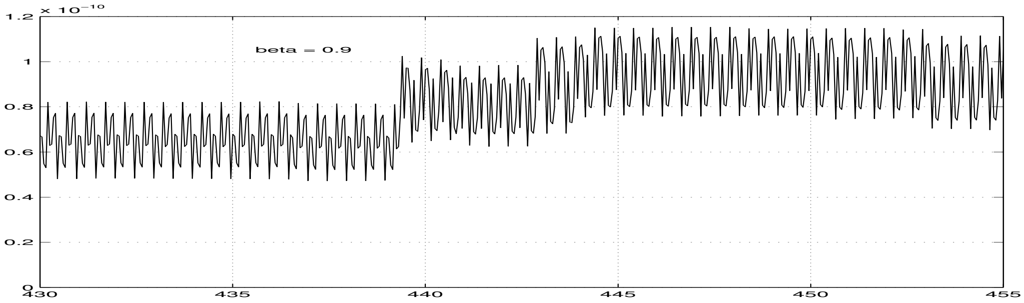
$\beta = 0.3$



$\beta = 0.5$

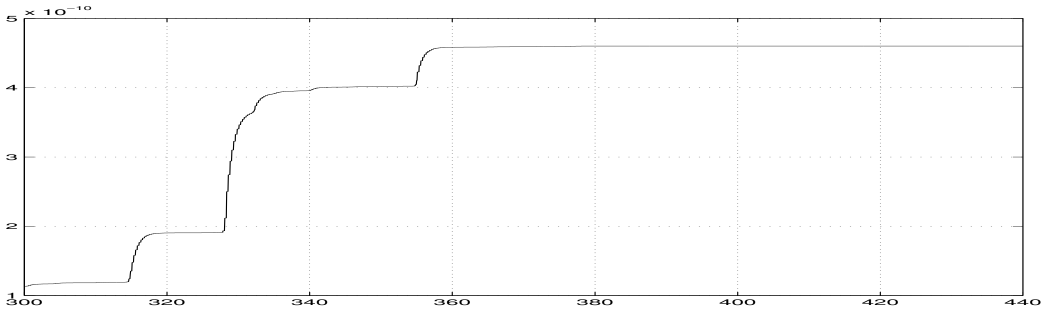


$\beta = 0.6$

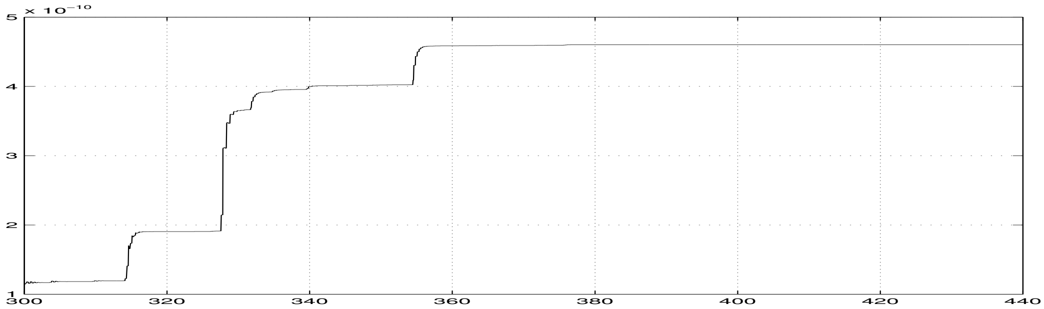


$\beta = 0.9$

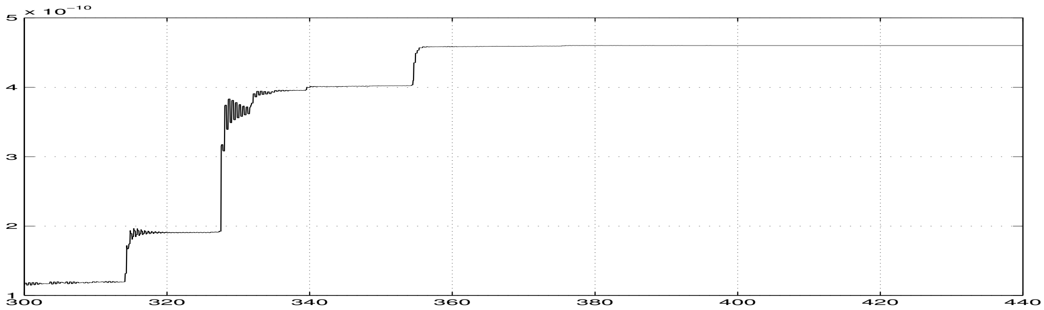
Figure 5.10: Received power levels (in Watts) at a base station vs. simulation time in seconds for random sample paths (offered traffic = 8.0 Erlangs/cell). The set of figures display the oscillatory behavior of soft dropping power control ($\overline{q}_j$ = -13 dB, $\hat{q}_j$ = -3 dB, $\hat{\Gamma}_j$ = -15 dB, and $\overline{\Gamma}_j$ = 8 dB) on users when $\beta > 1/(1+\delta) = 0.30$ and when every incoming call is admitted to the system and active calls are not dropped.



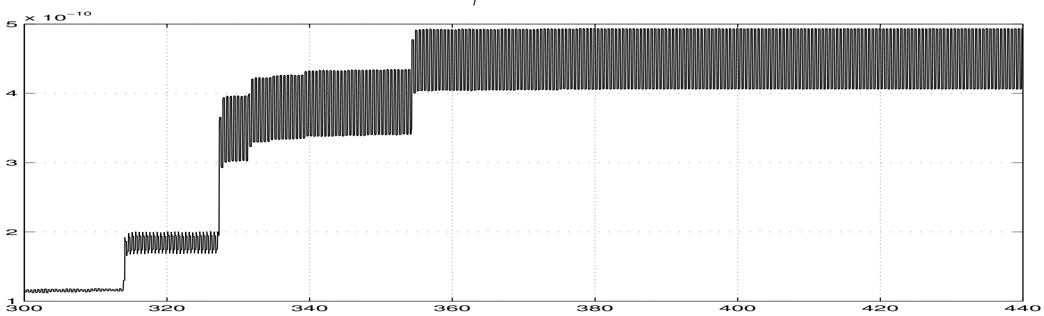
$\beta = 0.3$



$\beta = 0.5$



$\beta = 0.6$



$\beta = 0.9$

Figure 5.11: Received power levels (in Watts) at a base station vs. simulation time in seconds for random sample paths (offered traffic = 5.0 Erlangs/cell) with fixed number of users to be supported by the system. The set of figures display the oscillatory behavior of soft dropping power control ($\overline{q}_j$ = -13 dB, $\hat{q}_j$ = -3 dB, $\hat{\Gamma}_j$ = -15 dB, and $\overline{\Gamma}_j$ = 8 dB) on users when $\beta > 1/(1+\delta) = 0.30$ and when every incoming call is admitted to the system and active calls are not dropped.

Chapter 6

Discussion

6.1 Summary and Conclusions

In this thesis, we propose a new power control strategy for mobile radio systems. This scheme helps us tackle the detrimental effects of infeasibility on system performance, occasionally observed in iterative power control schemes that meet certain SIR requirements. The focus of the scheme is on the sharp rise in interference levels at the base when faced with such a problem.

The problem is identified and an algorithm for stationary users transmitting on a single channel is proposed in Chapter 2. Convergence of the iterative power control algorithm to a minimum power solution is proved by means of standard interference functions, such that every user has a signal quality that meets or exceeds the target SIR requirement. The convergence of the asynchronous and distributed power control iteration is valid under minimum and maximum power constraints.

The general system model employed for simulations is under discussion in Chapter 3. The various performance measures employed to observe the behavior of the system with the application of the new power control strategy are also described.

An integrated dynamic radio resource management (IDRRM) approach which combines all the sub-tasks of radio resource management is used to evaluate resource allocation schemes. In this work, the simulation tool employed to perform IDRRM helped us investigate the improvements of soft dropping power control scheme over fixed target SIR schemes, in an appropriate environment. The simulations are performed for a

TDMA/FDMA based GSM system and a spread spectrum-based CDMA system. The various radio resource management schemes employed for the systems are described extensively in Chapter 4 and Chapter 5 respectively. Simulation results are also discussed and investigated thoroughly.

The insights provided by the simulation results are as follows. Under the practical system constraints such as minimum and maximum power constraints, step change in transmitter power for every iteration, if any, and mobility of users, the system performs favorably in terms of capacity improvements, battery power reduction or signal quality improvements. The decision of the values that define the soft drop region are crucial and will influence the gain in system performance. For specified target SIR constraints of variable target SIR algorithm, the soft drop power threshold decides when the user starts aiming for a variable target. Hence, it is indirectly responsible for the reduction in the level of interference on a channel in the system. However there exists a trade-off between the fall in mean uplink transmitter power levels and the tolerable deterioration in the mean signal quality. Wider soft drop regions, that is aiming for a variable target SIR at relatively low transmitter powers, contribute to larger reductions in the interference level. However, there will also exist a modest deterioration in the signal quality. But the degradation of the quality does not nullify the gain in system performance due to considerable increase in the number of simultaneous users supported and the fall in users' transmitter powers. Narrow range of target SIRs does not give as high a gain in system performance as wider range of target SIRs, as long as the two limits are above the minimum signal quality requirements and the upper limit fixed to the fixed target SIR scheme value. Appropriate setting of the target SIR constraints can help improve the quality of the connection at the same amount of battery power consumption as common target SIR schemes. The system is robust to changes in the rate of convergence of the power control iteration, as long as the value of the β is not too low.

6.2 Further Studies

Further study is needed in the area of implementation of the power control strategy with delayed SIR information. The robustness of the algorithm to inaccurate SIR information or SIR estimation needs investigation. The rate of power updates required to adapt to the changing environment of the cellular network also needs to be understood.

A topic for further research would be to study the effect of Rayleigh fading on the performance gains. The results for an elementary CDMA system have encouraged similar implementation using more sophisticated simulation tools to evaluate the performance

References

[1] W. Tschirks. Effects of transmission power control on the co-channel interference in cellular radio networks. *Electrotechnik und Informationstechnik*, Vol. 106, no. 5, 1989.

[2] T. Fuji and M. Sakamoto. Reduction of co-channel interference in cellular systems by intra-zone channel reassignment and adaptive transmitter power control. *Proc. 38th IEEE Vehicular Technology Conference 1988*, pages 668-672, May 1988.

[3] T. Nagatsu, T. Tsuruhara and M. Sakamoto. Transmitter power control for cellular land mobile radio. *Proc. IEEE Globecom* pages 1430-1434, 1983.

[4] J. F. Whitehead. Signal-level-based Dynamic Power Control for Co-channel interference Management. *Proc. 43rd IEEE Vehicular Technology Conference 1993*, pages 499-502, May 1993.

[5] J. M. Aein. Power Balancing in Systems Employing Frequency Reuse. *Comsat Technical Review*, Vol. 3, no.2, Fall 1973.

[6] H. J. Meyerhoff. Method for computing the Optimum Power Balance in Multibeam Satellite. *Comsat Technical Review*, Vol. 4, no. 1, Spring 1974.

[7] R. W. Nettleton and H. Alavi. Power Control for Spread Spectrum Cellular Mobile Radio System. *Proc. 33rd IEEE Vehicular Technology Conference 1983*, pages 242-246, 1983.

[8] J. Zander. Performance of optimum transmitter power control in cellular radio systems. *IEEE Transactions on Vehicular Technology*, Vol. 41, no. 1, Feb 1992.

[9] J. Zander. Distributed co-channel interference control in cellular radio systems. *IEEE Transactions in Vehicular Technology*, Vol. 42, no. 4, November 1993.

[10] S. A. Grandhi, R. Vijayan, D. Goodman, and J. Zander. Centralized power control in cellular radio systems. *IEEE Transactions on Vehicular Technology*, Vol. 42, no. 4, November 1993.

[11] S. A. Grandhi, R. Vijayan, and D. Goodman. A Distributed Algorithm for Power Control in Cellular Radio Systems. 30th Annual Allerton Conference on Communications, Control and Computing, Monticello, Illinois, September 1992.

[12] S. A. Grandhi, R. Vijayan, R. Yates, D. G. Goodman, and J. M. Holtzman. Distributed Dynamic Resource Allocation. *Technical Report WINLAB-TR58*, Rutgers University, July 1993.

[13] S. A. Grandhi and J. Zander. Constrained power control in cellular radio systems. IEEE J. Sel. Areas Commun., 13(7):1341-1348, September 1994.

[14] S. A. Grandhi. *Power Control in Mobile Radio Systems.* PhD thesis, Rutgers University, 1994.

[15] G. J. Foschini and Z. Miljanic. A simple distributed autonomous power control algorithm and its convergence. *IEEE Transactions on Vehicular Technology,* 42(4), November 1993.

[16] D. Mitra. An asynchorous distributed algorithm for power control in cellular radio systems. In *Fourth WINLAB Workshop on Third Generation Wireless Information Networks,* 1993.

[17] S. V. Hanly. An algorithm for combined cell-site selection and power control to maximize cellular spread spectrum capacity. *IEEE J. Sel. Areas Commun.,* 13(7):1332-1340, September 1995.

[18] R. Yates, and C. Y. Huang. Integrated power control and base station assignment. *IEEE Transactions on Vehicular Technology*, Vol. 44, no. 3, August 1995.

[19] R. Yates. A framework for uplink power control in cellular radio systems. *IEEE J. Sel. Areas Commun.*, 13(7):1341-1348, September 1995.

[20] R. Yates, and C. Y. Huang. Constrained power control and base station assignment in cellular radio systems. *IEEE/ACM Transactions on Networking,* 1995.

[21] D. J. Goodman. Draft - A guide to Personal Wireless Communications, 1997.

[22] C. N. Chuah, R. Yates, and D. J. Goodman. Integrated Dynamic Radio Resource Management. *45th IEEE Vehicular Technology Conference VTC-95*, pages 584-588, May 1995.

[23] C. N. Chuah and R. Yates. Evaluation of a minimum power handoff algorithm. In *Sixth IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC '95*, pages 623-627, 1995.

[24] K. Chen. Integrated Dynamic Radio Resource Management of Wireless Communication Systems. *M. S. Thesis submitted to Graduate School, Rutgers University*, May 1996.

[25] P. Fleming, and A. Stolyar. Convergence properties of the CDMA reverse link power control algorithm.*45th IEEE Vehicular Technology Conference VTC-95*, May 1995.

[26] M. Almgren, H. Andersson, and K. Wallstedt. Power control in a cellular system. In *IEEE Vehicular Technology Conference VTC-94*, pages 833-837, May 1994.

[27] R. Beck, and F. W. Ho. Evaluation and Performance of field strength related handover strategies for micro-cellular systems, *3rd Nord. Sem. Dig. Mob. Radio*, Copenhagen, 1988.

[28] R. Vijayan and J. Holtzman. Analysis of handoff algorithms using nonstationary signal strength measurements, *Proc. Globecom '92*, December 1992.

[29] R. Vijayan and J. Holtzman. A model for analyzing handoff algorithms. *IEEE Transactions on Vehicular Technology*, August 1993.

[30] N. Zhang and J. Holtzman. Analysis of handoff algorithms using both absolute and relative measurements. *Proc. 44th IEEE Vehicular Technology Conference VTC-94*, pages 82-86, May 1994.

[31] P. Gaasvik, M. Cornefjord, and, V. Svensson. Different methods of giving priority to handoff traffic in a mobile telephone system with directed retry. Proc. IEEE Vehicular Technology Conference VTC-91, pages 549-553, May 1991.

[32] M.Gudmundson. Analysis of handover algorithms in cellular radio systems. Technical report TRITA-TTT-9107, Royal Institute of Technology, Sweden, 1991.

[33] D. Hong and S. Rappaport. Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures. *IEEE Transactions on Vehicular Technology*, Vol. 35, no. 3, pages 77-92, August 1986.

[34] W. Mende. Evaluation of a proposed handover algorithm for the GSM cellular system. *Proc. of 40th IEEE Vehicular Technology Conference*, pages 264-269, May 1990.

[35] An overview of the application of CDMA to digital cellular systems and personal cellular networks. Submitted to TIA-TR45.5 Subcommittee on March 28, 1992.

[36] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver Jr., and C. E. Wheatley III. On the capacity of a cellular CDMA system. *IEEE Tran. on Veh. Tech.*, Vol. 40, No. 2, pages 303-312, May 1991.

[37] K. S. Gilhousen, I. M. Jacobs, R. Padovani,and L. A. Weaver Jr. Increased capacity using CDMA for mobile satellite communications. *IEEE Trans. Select. Areas Commun.*, Vol.8, pages 503-514, May 1990.

[38] A. J. Viterbi. *CDMA-Principles of Spread Spectrum Communication*, Addison-Wesley, 1995.

[39] A. J. Viterbi *et al.* Soft handoff extends CDMA cell coverage and increases reverse link capacity. *IEEE J. Sel. A. of Commun.* 12(8), pages 1281-1288.

[40] H. Ochsner. Overview of the Radio Subsystem. *Proc. Digital Cell Radio Conf. (DCRC '88)*, pages 3a/1-12, Hagen, FRG, October 1988.

[41] A. Maloberti. Radio transmission interface of the Digital Pan European Mobile System. *Proc. 39th IEEE Vehicular Technology Conference VTC-89*, pages 712-717, May 1989.

[42] Michel Mouly and Marie-Bernadette Pautet. The GSM System for Mobile Communications, 1992 Edition.

[43] ETSI - European Telecommunications Standardization Institute. *GSM recommendations 05.08.*

[44] CT2 Plus, A proposal for a Canadian common air interface standard. Issue 2.0 submitted to Radio Advisory Board Canada Industry Comm. Working Group Radio Interface Standards, Dec. 1990

[45] R. Nettleton and G. Scholemer. A high capacity assignment method for cellular mobile telephone systems. In *Proc. IEEE VTC '89*, May 1989, pages 359-367.

[46] D. Cox and D. Reudink. Dynamic Channel Assignment in two-dimensional large-scale mobile radio systems. Bell Sys. Tech. J., pages 1611-1629, Sept 1972.

[47] L. Cimini, G. Foschini, and C-L I. Call blocking performance of distributed algorithms for dynamic channel allocation in microcells. *Proc. ICC '92*, June 1992.

[48] C-L I and P-H Chao. Local-packing-Distributed dynamic channel allocationat cellular base station. In *Proc. GLOBECOM '93*, December 1993.

[49] W. Eriksson and R. Bownds. Performance of dynamic channel allocation in the DECT systems. In *Proc.41st IEEE Vehicular Technology Conference '91*, pages 693-698, May 1991.

[50] A. Motley. Advanced cordless telecommunication service. *IEEE J. of Sel. Areas in Communication*, Vol. SAC-5:774-782, June 1987.

[51] H. Ocshner. Radio aspects of DECT. On *PROC. 4th Nordic Seminar Digital Mobile Radio Communication*, June 1990. Paper 6.4.