A REALISTIC MOBILITY MODEL AND ITS APPLICATION TO A RESERVATION-BASED CALL ADMISSION SCHEME FOR DS-CDMA CELLULAR SYSTEMS

by

Tuna Tuğcu

BS, in Computer Engineering, Boğaziçi University, 1993

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APPROVED BY:

Assoc. Prof. Cem Ersoy . . . .
(Thesis Supervisor)

Prof. Semih Bilgen . . . .

Prof. M. Ufuk Çağlayan . . . .

Assoc. Prof. Hakan Deliç . . . .

Prof. Oğuz Tosun . . . .

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ABSTRACT

A REALISTIC MOBILITY MODEL AND ITS APPLICATION TO A RESERVATION-BASED CALL ADMISSION SCHEME FOR DS-CDMA CELLULAR SYSTEMS

Call blocking and call dropping are the reasons for outage in mobile wireless systems. Guard channels can be allocated for handoff calls in each cell to give higher precedence to handoff calls over new call attempts. Since new call attempts may be rejected although there are free guard channels, the decrease in the call dropping rate is achieved at the cost of increased blocking rate. Therefore, the number of guard channels is an important metric that effects system performance.

In this thesis, we propose a call admission scheme that adjusts the number of guard channels dynamically. A reservation area is constructed for each active subscriber according to his speed, direction and recent mobility pattern. A reservation request, associated with a likelihood value, is sent to each candidate cell intersected by the reservation area. The number of channels to be reserved in each cell is obtained from the aggregation of the likelihood values in the received reservation requests. We have evaluated the proposed scheme against the classical scheme with fixed number of guard channels, and shown that the proposed scheme performs better in the sense that call dropping rate is reduced with lower cost.

We also propose a realistic mobility model that captures human behaviors from real life such as *moving-in-groups*, *conscious traveling*, *inertial behavior*, and the *non-pass-through* feature of the physical structures in the terrain. The mobility patterns of the subscribers are determined according to a given real map composed of various types of physical structures. We have evaluated the proposed mobility model against the way point model, and shown that the choice of the mobility model results in a significant difference in system performance.

ÖZET

GERÇEKÇİ BİR HAREKET MODELİ VE DS-CDMA SİSTEMLER İÇİN REZERVASYONA DAYALI BİR ÇAĞRI KABUL YÖNTEMİNE UYGULANMASI

Telsiz gezgin sistemlerde hizmet kesintisinin nedeni çağrı tıkanması ve çağrı düşmesidir. El değiştiren çağrılara, yeni çağrı denemelerine karşı öncelik vermek için her hücrede koruma kanalları ayrılabilir. Yeni çağrı denemeleri, boşta koruma kanalları olduğu halde reddedilebileceği için çağrı düşme oranındaki düşüş çağrı tıkanma oranındaki artışla elde edilir. Bu yüzden, koruma kanalı sayısı sistem başarımını etkileyen önemli bir ölçüttür.

Bu tezde, koruma kanalı sayısını devingen olarak ayarlayan bir çağrı kabul yöntemi öneriyoruz. Etkin her kullanıcı için kullanıcının hızı, yönü ve yakın geçmişteki hareket örüntüsüne göre bir rezervasyon alanı belirlenir. Rezervasyon alanıyla kesişen her aday hücreye, yakınlık değeri ile eşleştirilmiş bir rezervasyon isteği gönderilir. Her hücrede ayrılacak koruma kanalı sayısı gelen rezervasyon istekleri ile eşleştirilmiş yakınlık değerlerinin toplamından bulunur. Önerilen yöntemi sabit sayıda koruma kanallı klasik yöntemle karşılaştırdık ve önerilen yöntemin çağrı düşme oranını, çağrı tıkanma oranındaki artış açısından daha az masraflı olarak azalttığını gösterdik.

Bu tezde ayrıca, insanların gerçek yaşamdaki birlikte hareket etme, bilinçli yolculuk, eylemsizlik davranışı ve arazideki kimi yapıların içinden geçilmez özelliğini uygulayan gerçekçi bir hareketlilik modeli öneriyoruz. Kullanıcıların hareket örüntüleri farklı fiziksel yapılar içeren bir gerçek haritaya göre belirlenmektedir. Önerilen hareketlilik modelini yol-noktası modeli ile karşılaştırdık ve hareketlilik modelinin sistem başarımında önemli etkisi olduğunu gösterdik.

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LIST OF SYMBOLS/ABBREVIATIONS

a	Semi-major axis of the ellipse
b	Semi-minor axis of the ellipse
c	Distance from center of ellipse to any one of the two foci
d	Distance subscriber can travel during the reservation duration
r	Cell radius
w_1	Factor for the subscriber-cell center distance
w_2	Factor for the location of cell center with respect to the direction of the subscriber
A	Transmission power of mobile station
G	Number of reserved guard channels
I_o	Total uter cell interference
I_u	Outer cell interference due to a single subscriber
L	Likelihood that subscriber will visit the cell during the reservation period
M	Number of cells in service area
R	Data rate
S	Received signal power per MS at BS
S_N	Received signal power per MS at BS when N subscribers are active
W	Chip rate
α	Voice activation factor
β_1	Angle between the line that connects the subscriber to the cell center and x-axis
β_2	Direction of the subscriber
δ	Weight factor
κ	Distance between mobile and base stations
θ_t	Direction of the subscriber at time t
ξ	dB attenuation due to shadowing

AMPS	Advanced Mobile Phone System
BS	Base Station
CBP	Call Blocking Probability
CDMA	Code Division Multiple Access
CDP	Call Dropping Probability
CIM	Current Interference Margin
CNCL	Communication Networks Class Library
DS-CDMA	Direct Sequence CDMA
FCC	Federal Communications Commision
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FH-CDMA	Frequency Hopping CDMA
GoS	Grade of Service
GPS	Global Positioning System
GSM	Groupe Spécial Mobile - Global System for Mobile Communications Communications
HIM	Handoff Interference Margin
LPI	Low Probability of Intercept
MS	Mobile Station
PN	Pseudo-Noise sequence
QoS	Quality of Service
RPGM	Reference Point Group Mobility
SIR	Signal-to-Interference Ratio
TDMA	Time Division Multiple Access
TIM	Total Interference Margin
USDC	U.S. Digital Cellular

1. INTRODUCTION

Development in wireless technology has introduced cellular phones to daily life. The ease of communications provided with cellular phones has attracted so much public interest that research in wireless communications has exploded. The increase in the number of subscribers[1] together with the emerging wireless applications has tightened the constraints on the scarce resource of frequency. Better utilization of the frequency bandwidth is crucial to improve the system capacity and subscriber satisfaction.

Two major factors that define user satisfaction are the *CBP (call blocking probability)* and the *CDP (call dropping probability)*. CBP is defined as the probability that a new call request issued by the subscriber will be rejected because a channel cannot be allocated for the call. CDP, also called *forced call termination probability*, is the probability that the request to transfer an ongoing call from one cell to another is rejected due to insufficient spectral resources in the new cell, and the call is terminated without the will of the subscriber. In the literature, it is widely accepted that call dropping is more annoying than call blocking [1], [2].

It is possible to decrease CDP by reserving channels for possible handoffs. These channels are called *guard channels*. Since the guard channels are reserved for handoff calls, new call requests will not be granted if all channels except the guard channels are busy. Therefore, determining the optimum number of guard channels is a crucial issue for the system performance. If the number of guard channels is too high, many new call attempts will fail although there are free channels. On the contrary, if the number of guard channels is too low, many handoff events will fail resulting in a high forced call termination rate. Thus, there is a trade-off between call blocking and call dropping. The decision for the optimum number of guard channels is both time and space dependent. The number of guard channels depends on the location. For example, the highways are likely to receive more handoff calls than residential areas. The number of guard channels necessary for a cell may also depend

[1] Throughout this thesis, the term “subscriber” will be used for the human carrying the wireless equipment whereas “mobile” will be used for the equipment itself.

on the time of the day. For example, the city centers will be more likely to receive handoff calls during day time than nights. The optimum number of guard channels may also depend on random events like traffic congestion, accidents, or festivals. Therefore, assigning a predetermined number of guard channels to each cell will cause a high CDP in some cells and a high CBP in some others.

In order to decrease CDP without increasing CBP too much, one should reserve channels only in the cells on the future path of the subscriber. However, since the path that the subscriber will follow is independent of the planning of the spectral resources, it is not possible to exactly know the set of cells on his[2] way. However, a good estimation for this set can be made by considering the fact that subscribers move towards a destination instead of making random moves. Therefore, the path that a subscriber follows is the concatenation of multiple line segments towards the destination. A reservation area may be formed by considering this fact. Though not guaranteed, it will be very likely that the subscriber will remain in this reservation area in the near future.

In the literature, most of the previous work on guard channels assigns a fixed number of guard channels to each cell [3], [4], [5], [6]. As stated above, fixed number of guard channels is vulnerable to fluctuations in new call generation and handoff rates. Methods for variable number of guard channels have been proposed in [7], [8], [9], [10], [11]. The work in [7] and [11] is for TDMA/FDMA systems. The air interface is not specified in [10]. Only the work in [8] and [9] propose variable number of guard channels for CDMA systems. However, they have some deficiencies as will be discussed later. In [12], a scheme that borrows channels from stationary calls participating in handoffs in order to allocate them to handoff requests by moving mobiles.

In this thesis, we have devised a method for adaptive call admissions with channel reservations for DS-CDMA systems [13]. The mobility pattern of the subscriber in recent history is considered to estimate his mobility pattern in the near future and to set up the reservation area. Each reservation request is accompanied with a value representing how likely it is that the subscriber will visit that cell. Thus, instead of reserving one guard channel

[2]Throughout this thesis, “he” should be read as “he or she”, and “his” as “his or her”.

for each reservation request, we prefer being more thrifty on guard channels to help keep CBP at low values. The reservations are interference based since a DS-CDMA system is interference sensitive. Interference based reservations help avoid *instability* of the system. Instability occurs in a system when granting a call request, new call or handoff, results in the termination of some other ongoing call due to the violation of *SIR (Signal-to-Interference Ratio)* constraint. We have also devised a realistic mobility model to verify our proposed call admissions algorithm [14]. Our mobility model is realistic in the sense that the subscribers follow mutually independent patterns over the service area while capturing the "*moving in groups*" behavior of the society. Given a topographic map, the subscribers move on the streets and highways, respecting the existence of *non-pass-through* feature of the households. The subscribers are able to realize the "leave the house", "go to home" and "get on the highway from specific entry points" features of a human subscriber together with extra-ordinary features like "row across the Bosphorus". The call behavior patterns of a subscriber changes when the subscriber leaves the house to get on the street. None of the work in the literature has been evaluated with such detailed mobility patterns.

1.1. Contribution of the Dissertation

In this thesis, we investigate the methods for combating forced call termination, and propose a scheme that reserves guard channels on request. In the proposed scheme, new call requests to the system are granted by respecting these reservations, providing higher precedence to handoff calls over new call attempts. The aim of this thesis is to decrease the forced call termination rate at the expense of lower cost, in terms of increase in call blocking, with respect to the classical guard channel schemes.

In the proposed scheme, active mobile stations make reservation requests as the subscriber carrying the mobile station moves in the service area. The reservation area is determined according to the speed, direction and the recent mobility pattern of the subscriber. Together with the reservation requests sent to each candidate cell in the reservation area, a likelihood value is associated. The number of channels to be reserved in each cell is determined adaptively from this statistical accumulation of the likelihood values associated with the incoming reservation requests, as opposed to the fixed number of guard channels in the classical scheme. The shortcoming of the classical scheme is the possible call blockings in the cells with free guard channels. The proposed scheme decreases the possibility of such unnecessary call drops by reserving channels which will be required with high probability, and utilizing unnecessary guard channels for the new call attempts to achieve lower blocking probability. The proposed scheme benefits from the speed and direction information about the subscriber to establish the reservation area.

We also propose a novel mobility model, which is realistic in the sense that subscriber mobility patterns are based on given real maps. The proposed mobility model captures human behaviors in real life such as moving-in-groups, conscious traveling, inertial behavior and the non-pass-through feature of the physical structures in the terrain.

1.2. Structure of the Thesis

In the next chapter, an overview of cellular networks is given, and a short summary of the basics of DS-CDMA technology, only to the extent that relates to this thesis, is provided. Chapter 2 also discusses the previous work in the literature.

The proposed call admission scheme is discussed in Chapter 3. The definition of the construction of reservation area, calculation of the likelihood values and the call admission scheme based on reservations are the basic topics discussed in this chapter. Some of the details on these topics are given in the appendices.

We discuss the proposed mobility model in Chapter 4. The previous work in the literature on mobility models is also discussed in this chapter.

Chapter 5 provides the results of the experiments performed for the evaluation of both the call admission scheme and the mobility model, and elaborates on these results.

Finally, we conclude in Chapter 6, and discuss some future work.

2. WIRELESS COMMUNICATIONS

2.1. Reasons for a Cellular Infrastructure

The *capacity* of a wireless communication system is defined as the number of simultaneously communicating subscribers. Since a channel is allocated for each active subscriber,[3] the capacity of the system is determined by the number of available channels. The number of channels can be increased by reusing the frequencies over the service area. Since each frequency corresponds to one or more channels, reusing a frequency at some other location implies making new channels available at that location, resulting in more conversing subscribers and higher capacity.

Every piece of service area to which one or more frequencies is assigned is called a *cell*. Every cell is controlled by a single *BS (Base Station)*. However, one base station may control more than one cell. The transmission power of a *MS (Mobile Station)* is lower for a cellular network with respect to a network without any cellular infrastructure since the average distance between an MS and its controlling BS is much smaller. Lower transmission power results in lower interference, less power consumption and less harm to human body. The decrease in interference helps increase the system capacity. Lower power consumption helps increase the battery life which is a major problem in mobile communications. The system capacity increases with smaller cells at the cost of higher cost due to increased number of BSs [15].

Thus, the reasons for a cellular infrastructure can be gathered under the titles frequency reuse, lower interference and lower power consumption.

[3]By the phrase “active subscriber”, we mean subscribers who are currently conversing, and consuming spectral resources.

2.2. Economics of Hexagonal Cellular Layout

Although propagation considerations recommend the circle as a cell shape, the circle is impractical for design purposes, because an array of circular cells produces ambiguous areas, which are contained either in no cell or in multiple cells. On the other hand, any regular polygon approximates the shape of a circle and three types, the equilateral triangle, the square and the regular hexagon, can cover a plane with no gaps or overlaps. A cellular system could be designed with square or equilateral triangles, but, for economic reasons, the regular hexagonal shape has been adopted.

The economic motivation for choosing the hexagon is as follows: Assume a base station located at the center of each cell, the center being the unique point equidistant from the vertices. The vertices are in fact the worst-case points, since they lie at the greatest distance from the nearest base station. Restricting the distance between the cell center and any vertex to a certain maximum value helps to assure satisfactory transmission quality at the worst-case points. If an equilateral triangle, a square, and a regular hexagon all have the same center-to-vertex distance, the hexagon has a substantially larger area. Consequently, to serve a given total coverage area, a hexagonal layout requires fewer cells, hence fewer transmitter sites [16].

2.3. Basic Technologies in Wireless Communications

The communication between the BS and all subscribers in a cell share the same transmission medium, the air. In order to allow simultaneous transmission of all parties, a multiple access scheme must be employed. The scheme employed must be enable differentiating the transmission of the intended subscriber from all other transmissions. The communication between the BS and an MS is composed of at least one voice transmission accompanied with multiple control transmissions. Each of these transmissions is called a *channel*. The multiple access scheme provides numerous channels to be used for voice and control transmission. While the voice channels carry the voice signals, the control channels are used for control purposes such as paging, call request, synchronization, power control. When an active subscriber moves from one cell to another, a *handoff* (*handover*) takes place to pass the control of the MS from one BS to the other. Three basic multiple access schemes and/or their combinations are employed in wireless communication systems:

- **Frequency Division Multiple Access scheme - FDMA:** The frequency spectrum is chopped into multiple bands, each band constituting a separate channel. Channels are separated far enough to avoid cochannel interference [17]. Multiple subscribers can transmit *simultaneously*. However, each subscriber is limited inside a narrow channel with bandwidth equal to the overall system bandwidth divided by the maximum number of active subscribers.
- **Time Division Multiple Access scheme - TDMA:** Each subscriber has access to the whole frequency spectrum during his time slot. Thus, although the bandwidth is larger during the transmission period with respect to FDMA, subscribers transmit in turn.
- **Code Division Multiple Access scheme - CDMA:** Multiple subscribers can transmit over the whole frequency spectrum simultaneously. The transmission of each subscriber is encoded with a unique code, and it can be decoded at the receiver side using the same code as long as the required SIR constraints are met.

Numerous technologies have been developed by making use of one or a combination of these schemes. Early applications in the first generation of cellular telecommunication systems utilized the FDMA scheme with analog modulation. The second generation employed digital modulation, still for voice communications, utilizing either a TDMA over FDMA approach or the CDMA scheme. The CDMA scheme can also be applied as a CDMA over FDMA technique allowing multiple CDMA bands operating at different frequency bands. The CDMA scheme has also been selected as the air interface for the third generation of cellular systems. The basic difference of the third generation from the second is that in addition to voice communications, data communications at high speeds is also targeted.

The most well-known analog FDMA system is *AMPS (Advanced Mobile Phone System)*. Although AMPS was announced in 1971, it was not implemented until 1984. Initially, a 40 MHz band in the 800- to 900-MHz range was allocated by *FCC (Federal Communications Commission)* for analog systems. An additional 10 MHz band (*expanded spectrum*) was allocated due to the rapid growth of cellular traffic [18].

Two well-known TDMA/FDMA systems are *GSM (Global System for Mobile Communications)* and *USDC (U.S. Digital Cellular* or *IS-54)*. The allocated frequency spectrum is split into multiple frequency bands, resulting in an underlying technology of FDMA. Each frequency band in turn is time sliced to allow TDMA scheme over FDMA. Each time slot constitutes a channel. Since the MS transmits only during its time slot, the voice of the subscriber during the frame period is compressed into a time slot [19].

2.3.1. Spread Spectrum Technology

The term *spread spectrum* defines a class of digital radio systems in which the occupied bandwidth is considerably greater than the information rate. It was first introduced for military purposes over half a century ago since it copes with jamming very well in addition to being resistant to detection by eavesdroppers. Both goals can be achieved by spreading the spectrum of the signal to make it virtually indistinguishable from background noise. Only recently, the spread spectrum technique has been considered for civilian telecommunications. The well-known commercial application of spread spectrum is the IS-95 system. Originating from the military applications, IS-95 has incorporated many features to spread spectrum technology to achieve efficiency improvements.

The basic idea of spread spectrum system is to spread the signal to be transmitted by each MS by the unique code of the mobile so that the receiving BS can despread the signal back while treating the signals for all other mobiles as background noise. In analog FDMA and TDMA/FDMA hybrid systems, the frequency bands are planned by considering the worst case for all channels. On the other hand, in spread spectrum systems, better utilization of the spectral resources is achieved due to statistical multiplexing since all channels will not be exhibiting their worst case behavior simultaneously. Thus, spread spectrum systems benefit from higher capacity with respect to other systems.

As opposed to analog and other digital systems, spread spectrum systems can use the same frequency band in neighboring cells. This feature is called *universal frequency reuse*. In addition to increasing the efficiency of the spectrum usage, this feature also eliminates the chore of planning for different frequency allocation for neighboring subscribers or cells.

Thus, improper planning of the spectral resources does not constitute a problem in spread spectrum systems.

Power control ensures a high level of transmission quality while overcoming the *near-far problem* by maintaining a low transmitted power level for each mobile, and hence a low level of interference to other mobiles.

An important feature of spread spectrum systems is the mitigation of faded transmission through the use of a *Rake receiver* [19], [20] which constructively combines multipath components rather than allowing them to destructively combine as in narrowband transmission. Yet another benefit of the spread spectrum technique is its *soft capacity*. While TDMA/FDMA systems like GSM impose a fixed capacity determined by the number of frequencies assigned to each cell, a spread spectrum system enjoys variable capacity depending on the *current* value of interference by enforcing the limits. The spectrum of an information bearing binary stream is spread by combining with a complex waveform having special spectral characteristics [21]. This waveform may be:

- A series of pulses of the carrier at different frequencies in a predetermined pattern.
- A pseudorandom modulating binary waveform whose symbol (or chip) rate is a large multiple of the bit rate of the original bit stream.

The former technique is known as *FHSS (Frequency Hopping Spread Spectrum)* or *FH-CDMA (Frequency Hopping CDMA)* and the latter as *DS-CDMA (Direct Sequence CDMA)*.

FH-CDMA systems modulate the information onto a carrier using the conventional narrowband modulation, and shift the carrier frequency over the available bandwidth in a predetermined but pseudorandom sequence. A short dwell time on any particular frequency provides the *LPI (Low Probability of Intercept)* property while keeping the hopping sequence secret provides privacy. The antijam performance of a FH-CDMA system depends on the fraction of time spent on any particular frequency, i.e., the total number of frequencies available. Similarly, multipath tolerance is based on the effects of frequency-selective fading. An intentional carrier wave jammer, unintentional frequency-selective fading or interference from another subscriber obliterates large blocks of data in conventional narrowband modulation. However, since FH-CDMA spends only a short time at each frequency, only a few bits are errored, and error bursts are separated and randomized so that the errors can be corrected by *FEC (Forward Error Correction)* codes.

In DS-CDMA systems, the transmitter modulates the carrier by the data at bit rate, R, and the spreading code at a much higher chip rate W. The despreader in the receiver modulates the signal again by the identical spreading code. Provided that the codes are perfectly synchronized, the despreader will produce the same signal as in the input of the spreader. Thus, the signal energy, which was spread over W Hz in the channel, is collected into a bandwidth of R Hz by the despreader. Neither the spreading nor despreading process affects the spectral density of additive white noise.[4]

2.4. An Overview of the DS-CDMA Technology

2.4.1. Basic Idea

The basic difference of CDMA from the traditional multiple access schemes is in the way spectrum is partitioned. Instead of partitioning time (TDMA) or spectrum (FDMA) into disjoint slots, CDMA allows all mobile stations access the whole spectrum simultaneously by assigning a different instance of the noise carrier. The waveforms of the mobile stations are almost orthogonal. The major benefit of using noise-like carriers is that the sensitivity of the system to interference is fundamentally altered. The shortcoming of the traditional time slotted and frequency slotted systems is that a frequency reuse ratio that satisfies the *worst-case* interference ratio must be employed [22]. However, only a small fraction of the subscribers experience that worst-case scenario. In CDMA systems, each transmitter spreads its signal over its own noise carrier, and the receiver correlates its input with the desired noise carrier, enhancing the signal at the detector. The transmitted signal can be reformed at the receiver side as long as this enhanced signal overcomes the aggregate noise from other subscribers. Owing to the use of noise-like carriers, the effective noise in the

[4]Starting from this point in the thesis, the acronym “CDMA” will be preferred instead of “direct sequence spread spectrum” which has attracted more attention than “frequency hopping spread spectrum” systems.

system becomes the sum of the *spreaded* signals of all other users. Thus, CDMA systems are sensitive to the average interference while the traditional systems are sensitive to the worst-case interference.

2.4.2. Spreading/Despreading

In DS-CDMA systems, multiple users access the same frequency by means of the *PN (Pseudo-Noise) sequences*. An m-bit PN generator produces $2^m - 1$ different codes. Out of these codes, only m codes, called orthogonal codes, are assigned to m subscribers. The function of the PN code is to spread the data over the entire transmission band while uniquely identifying each mobile station. Spreading is implemented by a two-input exclusive-OR gate [23]. The input signal, which is a low speed data signal with narrow power spectrum, is exclusive-ORed with a high-speed signal, which is generally a PN sequence with wider power spectrum. The composite signal has the same transmission rate as the high-speed signal, since the latter has a wideband power spectrum, but a lower amplitude because the total energy is constant. Despreading is the process of recovering the data transmitted from the composite signal. Similar to spreading, despreading is also implemented with an exclusive-OR gate. The received composite signal is exclusive-ORed with the same PN sequence to get the data signal back.

The ratio of bit energy to the noise power spectral density (Figure 2.1) is given by

$$\frac{E_b}{N_o} = \frac{\frac{S_N}{R \cdot \alpha}}{N_t + (N-1) \cdot \frac{S_N}{W} + \frac{I_o}{W}} \tag{2.1}$$

where,

E_b is the energy per bit,

N_o is the noise power spectral density,

N is the number of active subscribers,

S_N is the signal power per mobile at the base station of a cell with N active subscribers,

R is the data information rate,

W is the transmission bandwidth,

α is the voice activation factor,

N_t is the thermal noise spectral density,

I_o is the outer cell interference created by active subscribers in the surrounding cells.

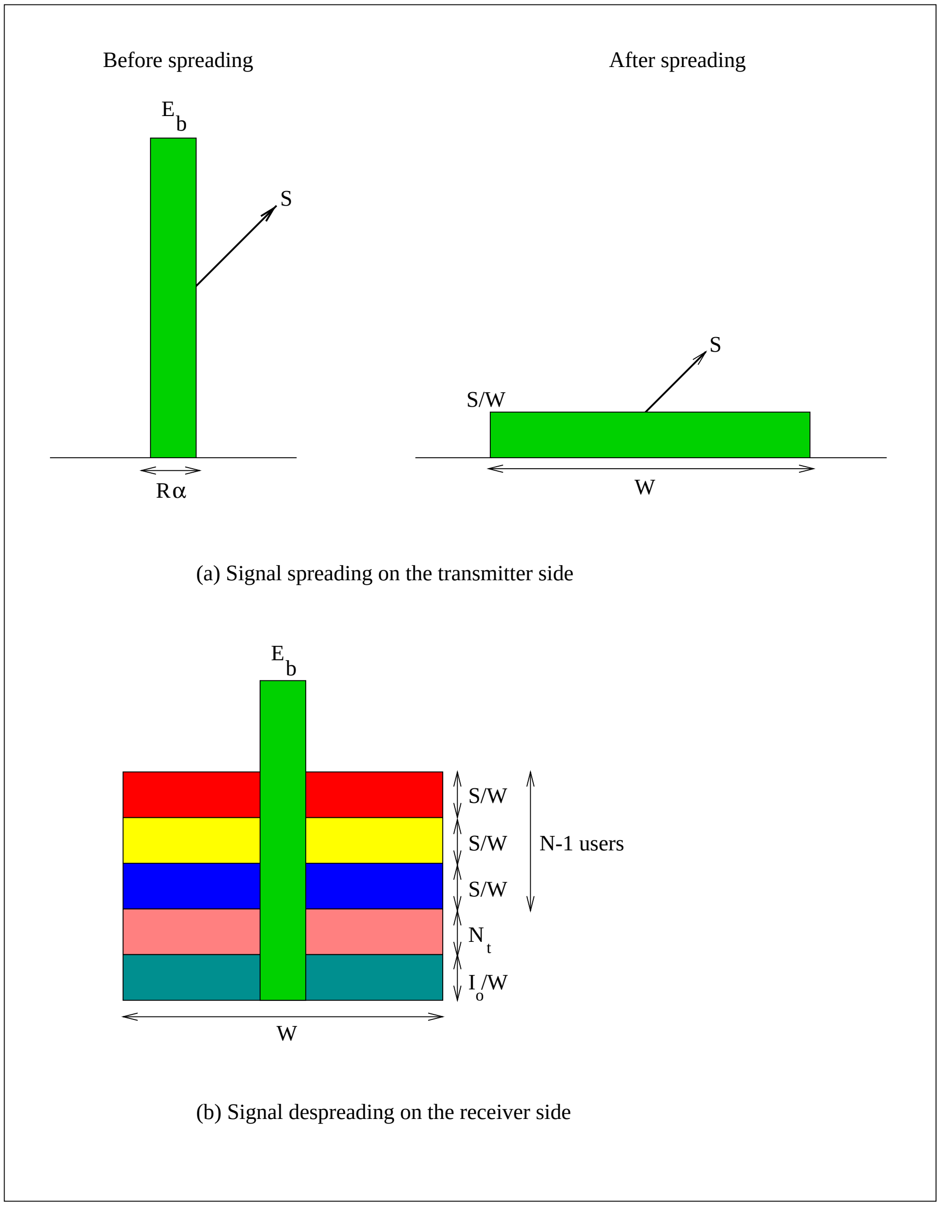


Figure 2.1. Signal spreading/despreading in terms of energy

2.4.3. Channels and System Capacity

When a MS is turned on, it acquires synchronization from the network. Following the synchronization, MS obtains information like cell identities, spreading codes, access channel and neighboring cell lists [24]. If the call is generated by the network, the network pages MS. After synchronization, MS initiates the connection setup through a random access message.

The connection setup is completed by an access grant message from the network, and the call proceeds on a traffic channel. Control information such as measurements and signalling data are transmitted throughout the connection. The details on channels used in CDMA systems are given in [23], [24].

As opposed to the traditional TDMA and FDMA systems, the system capacity, i.e., the maximum number of active subscribers in the system, is not hard limited, because a call request is granted as long as the required E_b/N_o ratio is maintained. A CDMA system is, therefore, said to have a *soft capacity*, and the capacity is time-variant [19].

2.4.4. Near-Far Problem and Power Control

The reason CDMA was considered as inappropriate for mobile radio is the *near-far problem*. If all the subscribers were transmitting with the same power, the received signal power for the subscribers close to the base station would be much higher than the received signal power for the subscriber that are far away due to the propagation path loss. To accommodate the farthest subscribers, the spreading bandwidth would have to be very wide, even worst than the most inefficient FDMA or TDMA system. This is why CDMA technology was not considered for any system, except the geosynchronous satellite environments, where the path loss spread is relatively small.

Power control was introduced to overcome the near-far problem [21]. With the power control mechanism employed, each subscriber transmits at *required* power level, instead of all subscribers transmitting at the power level for the farthest subscriber. The key idea is that the received signal power of each mobile station at the base station is roughly equal. In the reverse link open-loop power control, each mobile computes the relative path loss and compensates the loss by adjusting its transmission power. On the other hand, in the closed-loop power control, the base station drives each mobile with power-up and power-down commands explicitly. In the forward link direction, the base station controls its transmission power to let mobiles overcome fading, interference and *BER (Bit Error Rate)*. The base station reduces its transmission power while each mobile station computes the *FER (Frame Error Rate)*. When the mobile station detects one per cent FER, it sends a request so that the base station stops the power reduction [22], [23].

2.5. Related Work on Call Admissions

In this section, we discuss the related work on call admission schemes. The related work in literature about mobility models is discussed in Section 4.1.

In [3], Katzela and Naghshineh give an extensive survey of channel assignment schemes. Some of these schemes employ the channel reservation idea for TDMA/FDMA hybrid systems. Call admissions schemes with fixed number of guard channels for TDMA/FDMA systems have been proposed in [25]-[32]. The problem with call dropping rate may be solved to some extent by assigning different number of guard channels to each cell. However, since subscriber mobility patterns are time variant, in addition to being space variant, the idea of different number of guard channels also fails. Therefore, using fixed number of guard channels causes the system to be vulnerable to fluctuations in new call generation and handoff rates.

The multi-tier approach is considered in [33]-[40] to handle fast moving subscribers in the higher tier so that they encounter less handoffs. However, since the boundaries in the higher tiers are fixed, many handoffs still occur at the boundaries whereas the interior regions are free from handoff. In [4], Gavish and Sridhar propose *Threshold Priority Policy (TPP)* against *Cutoff Priority Policy (CPP)* in which a new call is accepted only if the number of new calls is below a certain threshold as opposed to a limit on the total number of calls as in CPP. Gavish and Sridhar implement reservation in terms of fixed number of guard channels without specifying the underlying air interface, and use a very simple model to evaluate the results. Their proposal is based on the number of channels without considering the interference constraints, and therefore, it is not appropriate for CDMA systems. In [8], Ma *et al.*, introduce *soft guard channels* based solely on the number of channels for CDMA systems. However, Ma *et al.*, disregard the soft capacity and interference sensitivity of CDMA, and also, they do not specify how the reservation area is determined. In [11], Levine and Akyıldız introduce the shadow cluster concept, similar to the reservation area proposed here, for TDMA/FDMA hybrid systems. Levine and Akyıldız do not benefit from the location information of the subscriber, and justify their work using analytical methods without considering the mobility patterns in real life. Levine and Akyıldız base their scheme on the side from which the mobile terminates the cell, and therefore, propose a scheme that depends on hexagonal cellular structure.

In [5], Shin *et al.*, propose an interference-based channel assignment scheme with reservations. The number of guard channels in their proposal is also fixed. We have extended their idea with the reservation scheme to adjust the number of guard channels adaptively. The work of Liu and Zarki [6] is similar to the work of Shin *et al.*, except that Liu and Zarki base the reservations on signal-to-interference ratio (SIR) as opposed to interference as in [5]. However, as Shin *et al.*, have pointed out, the proposal of Liu and Zarki is inconsistent with reality since SIR is kept constant by the power control mechanism.

In [10], Kim *et al.*, propose a dynamic channel reservation scheme in which they consider only the new call and handoff arrival rates at a cell, excluding the mobile direction information. Since Kim *et al.*, consider the arrival rates to the cells, it is possible that, in spite of the reservations made, the call of a subscriber who moves to a cell which does not receive much handoff requests may be dropped. On the other hand, some calls may be unnecessarily blocked in other cells due to sudden fluctuations in the new call and handoff arrival rates. We overcome their deficiency of useless reservations made in neighbor cells not on the moving direction of the mobile. In [12], Lee and Cho propose a scheme that borrows channels from stationary calls participating in handoffs in order to allocate them to handoff requests by moving mobiles. However, their approach fails if the signals of the subscriber from whom the channel is borrowed encounters fast fading since such subscribers cannot benefit from receiver diversity. In [9], Hou *et al.*, classify the subscribers into two groups, high-speed and low-speed, and draw the influence curve, analogous to our reservation area, based on dwell time and subscriber speed, disregarding the mobility pattern of the mobile. Hou argues that a subscriber is more likely to request a handoff in the far future after it enters a cell. However, this argument violates the fact that subscriber mobility is independent of wireless resources. In cases of *ping-pong effects*, where a subscriber switches between two cells frequently, this phenomenon will lower the system performance.

3. THE PROPOSED SCHEME

3.1. Motivation and the Basic Idea

In Section 2.1, it has been discussed that the main reason for a cellular layout is the efficient use of the scarce spectral resources to increase the system capacity. We consider only the uplink channel since it is the bottleneck in cellular systems [41], [42]. Due to the uneven distribution of the subscribers over the terrain, some parts of the service area will be more heavily loaded. Therefore, call attempts of the subscribers in such parts of the terrain will be more vulnerable to blocking and dropping with respect to the subscribers in other parts of the terrain. This space-dependence of call blocking and dropping events is an undesired situation. Since call dropping and call blocking are the main parameters in system performance evaluation, techniques for reducing such undesired cases should be considered in the system design.

Call dropping occurs when an active subscriber enters a cell where he cannot be granted a channel due to insufficient spectral resources. Only *active* subscribers on-the-move who enter a cell, which is crowded with other active subscribers, will suffer the undesired event of call dropping. In a cellular system, a fast moving subscriber will switch from one cell to another very often, resulting in shorter *sojourn* times, and therefore, he is more likely to be subject to call dropping. Needless to say, the speed of the subscriber does not constitute a problem as long as the subscriber is not active. In the literature, call dropping is accepted to be more annoying than call blocking [1], [43]. Therefore, system designers should take precautions to lower CDP, even at the expense of increasing CBP up to some extent.

If a channel can be reserved in the cell to which the subscriber will move soon, the forced call termination event may be avoided. In order to help decrease the CDP all over the service area, some number of channels can be reserved in each cell as guard channels. These channels will be used only for handoff calls arriving from neighboring cells, resulting in some new call requests being blocked although there are free guard channels. Thus, CDP can be decreased by causing an increase in CBP. To keep the increase in CBP at a reasonable level, the number of guard channels must have an upper bound. In other words, the number of guard channels defines the trade off between CDP and CBP. Since the subscriber mobility is independent of the management of wireless resources and the future path of the subscriber cannot be known exactly in advance, the number of guard channels to be reserved can be improved with mobility prediction for the subscribers.

The basic idea behind the proposed scheme is to estimate the region in which a fast moving subscriber may reside in the near future so as to minimize CDP. We will call this region as the *reservation area*, because CDP can be lowered by making reservations in this region. The reservation area can be simply constructed as a circular region with the center of the circle coinciding with the current locus of the subscriber. However, such a reservation area does not say much about the future mobility pattern of the subscriber, resulting in too many redundant reservations. Since redundancy in reservation causes an increase in CBP, one would like to trim out the redundant parts of the reservation area. This trimming can be achieved only to some extent since the exact future mobility pattern of the subscriber cannot be known. By estimating the direction of the subscriber in the near future, the reservation area can be narrowed from a circle down to an ellipse. Furthermore, overlapping one of the foci, instead of the center, of the ellipse with the current locus of the subscriber will provide more room in the forward direction instead of wasting unlikely portions behind (Figure 3.1). Assuming the service area is represented in a coordinate system, the size and shape of the reservation area may be better arranged by considering the following mobility features of a human subscriber:

- Subscribers do not make random moves. Instead of changing his direction and speed frequently, a subscriber tends to keep his direction towards his destination, approximately at the same speed.
- If the subscriber has been changing his direction very often in the recent history, he is likely to do so also in the near future. As a corollary, a subscriber who did not change his direction in the recent history frequently is more likely to show the same behavior in the near future. For example, a subscriber walking inside a mall will be changing his direction very often. However, a subscriber driving down the highway is more likely to drive on a straight line in the near future.

- The likelihood that a subscriber will be at a specific point in the near future is directly proportional to the distance between the specified point and the current location of the subscriber.
- The current location of the subscriber and his current direction determine the position and orientation of the ellipse, i.e., the angle between the major axis of the ellipse and the abscissa axis of the coordinate system.
- The speed of the subscriber, together with the frequency of changes in direction in the near past, determine the range of the reservation area on the major and minor axes.

The reservation area is determined based on the current location and velocity vector of the subscriber in addition to the change in the direction of the subscriber in the recent history (Figure 3.1). The region is simply drawn as an ellipse with the subscriber located at one of its foci. The shape of the ellipse is determined according to the factors stated above. The subscriber is likely to visit a cell intersected by the elliptical reservation area.

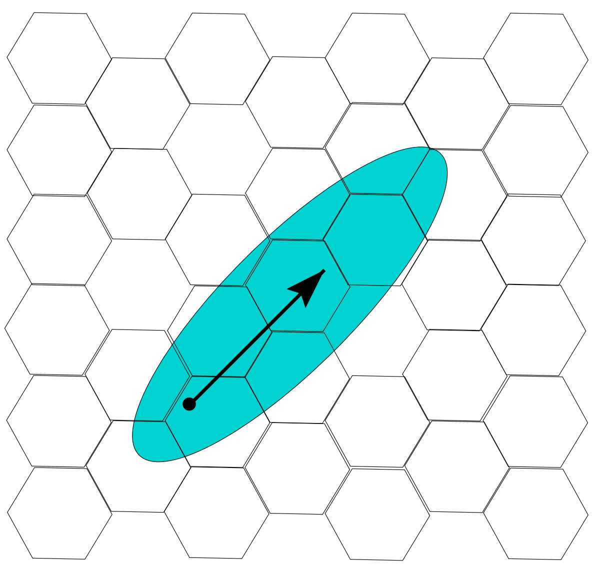


Figure 3.1. Elliptical reservation area constructed according to locus and direction of the subscriber

In the proposed scheme, the controlling base station of the mobile issues a reservation request to each cell intersected by the reservation area, called a *candidate cell*, on behalf of the subscriber. The call request, either a new call or a handoff call, can be granted a channel as long as there are enough resources in the controlling cell, even if some of the reservation requests have been rejected by the candidate cells, because it is not certain that the subscriber will go there. Furthermore, the reservation duration and the minimum acceptable CDP value can be included in the *QoS (Quality of Service)* bargaining [44]. Every incoming reservation request to a candidate cell is evaluated by the base station of the candidate cell against the interference constraints. A reservation request is granted only if the interference constraints would not be violated if the reserved channel was being actually used. In the previous adaptive reservation schemes in the literature [8], a guard channel is reserved for each reservation request. Since the candidate cell set is established by estimation, it is highly probable that some of the reservations will be redundant. In order to avoid vast increases in CBP due to redundant reservations, we assign a likelihood value to each reservation request. The likelihood value associated with each reservation request represents how likely it is that the subscriber may move into the candidate cell in the specified reservation duration. The likelihood value is determined by the distance of the subscriber to the cell center, and the closeness of the cell center to the direction of the subscriber. Thus, candidate cells that are close to the current locus of the subscriber and on the moving direction of the subscriber are favored to the cells that are far or behind the subscriber. The number of guard channels reserved in a cell is proportional to the sum of the likelihood values associated with the channel reservation requests received by that cell. Thus, the proposed scheme allows different number of guard channels to be reserved in each cell in the service area while saving on the number of guard channels by considering the likelihood values. Furthermore, the number of guard channels reserved is decreased from the number of reservation requests to the statistical accumulation of the reservation requests with respect to the likelihood values.

3.2. Implementation Issues

In order to implement the proposed scheme we have to make assumptions on determining the location, speed and direction of the subscriber. The speed and direction information can be easily derived as long as the locus of the subscriber is known. We assume that the locus of the subscriber can be obtained by means of *GPS (Global Positioning System)* and/or array antennas [45]. The decrease in the prices and size of the GPS devices has made this assumption feasible. The diversity in the array antennas can also be used for this purpose, especially for the subscribers indoors. Furthermore, locating the subscriber has been specified as a requirement by FCC [46].

It is assumed that, as opposed to the scarceness of the wireless resources, the resources in the wired portion of the network are in surplus and cheap. Therefore, we neglect the cost of reservation messages. We also assume that perfect power control is established.

Another assumption is the insertion of a power strength measurer in front of the correlators in the base station hardware in order to measure the current interference in interference-based reservation of the guard channels. This assumption is made also in [5], and is easy to satisfy since it requires a modification only at the service provider's premises.

The final assumption is on the cellular layout. We assume that the service area is covered with regular hexagons of the same radius. This assumption is made solely for the sake of simplicity in determining which cells are intersected by the reservation area. Furthermore, the cell boundaries are easily calculated in the mobility simulator for hexagonal cell layout. The proposed reservation scheme is completely independent of the cellular layout. We also assume that each base station is located at the center of its cell, equipped with omni-antennas.

We keep the mobile station responsible for gathering the location information to build up its recent mobility history. However, if the mobile location is to be tracked by means of array antennas instead of a GPS system, the controlling base station may gather the location information on behalf of the mobile station, and pass this information to the new controlling base station in case of handoff. This will help keep the load in the air interface due to location information at a low level.

The reservation area is constructed when a subscriber initiates a call, and it is updated periodically and in case of handoffs. The period of the reservation area construction determines the accuracy of the reservation area and the overhead in the fixed network between the base stations. We have used a period of 15 sec in the experiments made. The controlling base station of each active mobile station is responsible for constructing and maintaining the reservation area for the mobile station. The base stations are also responsible for handling the reservation requests coming from other base stations. During the construction of the reservation area, the calculation of the angle between the line that connects the subscribers current location to the center of the candidate cell and the abscissa axis of the coordinate system (Equation 3.5) will be made by the base station. The calculation of the angle between the current direction of the subscriber and the abscissa axis of the coordinate system will be made by either the base station or the mobile station, whichever gathers the location information. There is no additional requirement from the *MSC (Mobile Switching Center)* except for the transmission of reservation requests between base stations.

3.3. Constructing the Reservation Area

The reservation area represents the region in which the subscriber may reside during the reservation duration. It is an elliptical region, shaped and sized according to the reservation duration and the mobility pattern the subscriber has been following, that surrounds the current locus of the subscriber. Although past mobility pattern of the subscriber is considered in the construction of the reservation area, it is completely independent of the mobility simulator, i.e., the reservation area is constructed not by knowing, but by guessing the future direction of the subscriber.

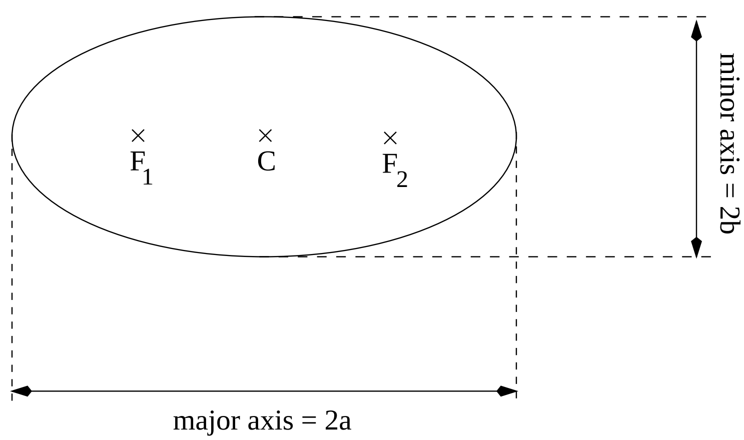


Figure 3.2. Basic metrics of an ellipse

The basic metrics that define an array are presented in Figure 3.2. An ellipse can be defined by its size on the major and minor axes, and one of its two foci [47]. While constructing the elliptical reservation area, we overlap the subscriber's current location with one of the foci and the orientation of the major axis with the direction of the subscriber, from the current locus of the subscriber towards the second focus. Since all geometric formulation about ellipses is based on the assumption that the major axis is parallel to the abscissa axis, rotation must be applied for all ellipse formulas to be used.

Having determined the location and orientation of the ellipse from subscriber coordinates and direction, determining the size of the ellipse on both the major and minor axes will complete the definition of the ellipse, thus the reservation area. The size of the ellipse on the major axis is defined by the speed of the subscriber and the reservation duration. A priori, the reservation area of a subscriber who is driving in a car will be *longer* than that of a pedestrian walking on the streets. The width of the reservation area is derived from the length of the ellipse and the estimated change in the direction of the subscriber. The inclusion of the length on the major axis in the calculation of the width on the minor axis implies that the width depends on the speed of the subscriber and the reservation duration, in addition to the estimated change in direction. The width determines whether the reservation area will be narrow region in the current direction of the subscriber, or a wider region, resembling a circle, around the subscriber. The former represents a case where the subscriber is not expected to change his direction, whereas the latter represents a case where it is difficult to guess the direction in which the subscriber may move. The former case generally applies to subscribers driving on the highways, and the latter case applies to pedestrians and drivers on small streets.

The estimation of the change in direction is made by considering the mobility pattern of the subscriber in the recent history. A *weighted sum* of the change in the direction of the subscriber is used to estimate the change in the direction of the subscriber. The reader should note that the aim of the estimation is not to determine where the subscriber will go in the next step, but to determine the width of the array. If the estimated change in the direction is close to 0^o, the reservation area will be a narrow ellipse. Otherwise, if the estimated change in the direction is close to 90^o, the reservation area will be distorted to a circle. Estimated values above 90^o will be truncated down to 90^o, since this value represents the worst case for the estimation, i.e., no estimation at all. In order to prevent the ellipse shrinking to a straight line, an offset of 30^o ($\pm 15^o$ error margin) is used for the estimated value. Thus, the estimated value of the change in the direction is calculated as

$$\widetilde{\triangle\theta_{t+1}} = \frac{\sum_{i=t}^{t-T} \triangle\theta_i \cdot \delta^{t-i}}{\sum_{i=t}^{t-T} \delta^{t-i}} \tag{3.1}$$

where,

t is the current time,

θ_t is the direction of the subscriber at time t,

$\widetilde{\triangle\theta_{t+1}}$ is the estimated change in direction at time $t+1$,

$\triangle\theta_i$ is the change in direction at time i,

T is the length of history considered for the estimation,

δ is the weight factor (less than 1).

The length of the ellipse on the major axis is calculated as

$$k = \frac{\widetilde{\triangle\theta_{t+1}} + \frac{\pi}{6}}{\frac{\pi}{2} + \frac{\pi}{6}} \tag{3.2}$$

$$2 \cdot a = \frac{2 \cdot d}{k^2} \cdot \left(1 - \left|\sqrt{1-k^2}\right|\right) \tag{3.3}$$

where,

a is the semi-major axis

d is the distance subscriber travels with his current speed during the reservation period

(The reader is referred to Appendix A for the derivation of Equation 3.3.)

Finally, the width of the ellipse is calculated as

$$2 \cdot b = k \cdot 2 \cdot a \tag{3.4}$$

After the reservation area has been set up as an ellipse, the cells that are intersected by the reservation area must be determined to find out the set of base stations to which a reservation request will be sent. For the cells which are at least 50 per cent covered by the reservation area, this is trivial; the center of the cell must be inside the ellipse. However, for

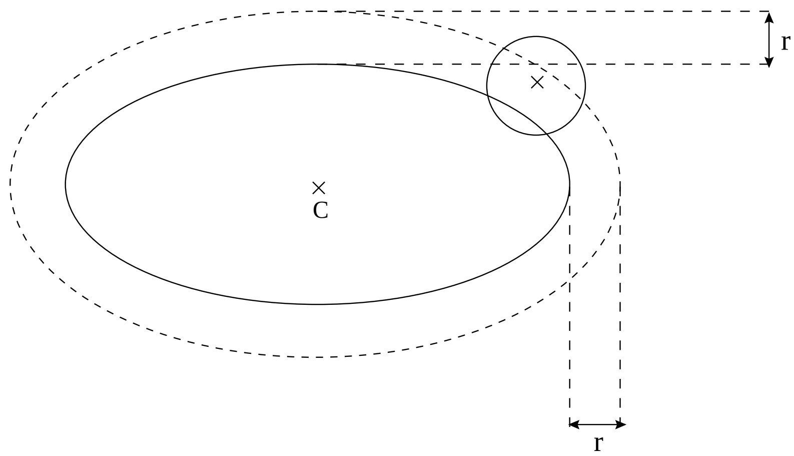


Figure 3.3. Finding whether the reservation area intersects a cell

the cells that are *slightly touched* by the reservation area, we have to employ the following trick. First of all, for the sake of simplicity, we approximate the regular hexagon shaped cell with its circumscribing circle. Thus, in very few cases, some cells that are very close to the reservation area, but not intersected by the reservation area will be considered to intersect with the reservation area, i.e., the reservation area will be over-estimated. However, since the reservation area is an approximation such an error may be disregarded. A new ellipse concentric with the ellipse representing the reservation area is drawn such that the semi-minor and semi-major axes of the new ellipse are both larger than that of the reservation area by R, the *cell radius* (Figure 3.3). The center of the circle must be inside the outer ellipse for any circle intersected, partially or completely, by the inner ellipse. Thus, the reservation area is constructed and the set of candidate cells is established. The next step is to calculate the likelihood values for each candidate cell and make the reservation request to the base station of the candidate cell.

3.4. Calculating the Likelihood Value

The reservation area can possibly intersect multiple candidate cells. However, all candidate cells are not equally likely to be visited by the subscriber. Therefore, a likelihood value is associated with each reservation request to specify how likely it is that the subscriber will visit that candidate cell. Candidate cells that are close to the current locus of the subscriber and/or on the moving direction of the subscriber are more likely to be visited than those behind and/or far. Considering the two factors of direction and distance, the likelihood value can be formulated as

$$L = w_1 \cdot \left(1 - \frac{subscriber\,to\,cell\;center\;distance}{2 \cdot a + r}\right) + w_2 \cdot \left(1 - \frac{|\beta_1 - \beta_2|}{\pi}\right) \quad (3.5)$$

where

L is the likelihood that the subscriber will visit the candidate cell during the reservation period,

w_1 is the factor for the subscriber-cell center distance,

w_2 is the factor for the location of the cell center with respect to the direction of the subscriber,

a is the semi-major axis of the ellipse representing the reservation area,

r is the cell radius,

β_1 is the angle between the line that connects the subscriber to the cell center and x-axis,

β_2 is the direction of the subscriber.

The reader should note that the effect of the speed of the subscriber is taken into account by utilizing the semi-major axis of the ellipse. Also, the term multiplied with w_2 normalizes the difference between the two angles with respect to π. The number of reserved channels reserved in each cell is calculated by summing the likelihood values in all of the reservation requests received by that cell. This way, the number of reserved channels reserved by a cell receiving multiple reservation requests with low likelihood values will be less than the number of reservation requests. Hence, the idea of using likelihood values in reservation requests helps decrease the number of reserved channels, and therefore also limit the increase in the blocking probability. In [8], a new guard channel will be reserved for each reservation request.

3.5. Interference-Based Reservation of a Channel

Reserving a channel in an FDMA or FDMA/TDMA system is straight forward. Since the number of channels is fixed, some of the nominal channels are marked as reserved, and they are not made available to new call requests. However, CDMA systems have soft capacity, which means the number of channels is not fixed. Therefore, in a CDMA system one cannot talk about available channels. Since CDMA systems are interference sensitive, a call request, either a new call or a handoff call, is granted a channel as long as the interference constraints are not violated. Consequently, different approaches must be used for channel reservation in CDMA systems. In [6], a *SIR*-based approach is proposed, in which a call request is granted a channel if the SIR constraint is not violated. However, since CDMA systems try to keep SIR at a constant level, their approach is not applicable. In [5], Shin *et al.*, propose an interference-based approach. In this thesis, we make use of this approach by extending their scheme, which makes use of fixed number of guard channels in every cell, to support adaptive number of reserved channels.

The basic idea in interference-based reservation scheme is to include the *to-be interference due to reserved channels* in the calculations, i.e., while making the call admission decision, the interference that would be created if the reserved channels were in use is also considered. A new call request is granted a channel only if the aggregation of the interference due to ongoing calls and the reserved channels, together with the outer cell interference and thermal noise is below the total allowed interference level, *TIM (Total Interference Margin)*, in the cell. On the other hand, a handoff call request is evaluated by considering only the interference due to ongoing calls, outer cell interference and thermal noise. In this way, the handoff calls are given priority over the new call requests. The implementation of the channel reservation based on interference is given in [5]. We briefly discuss this implementation below, and extend it with adaptive number of guard channels in the following subsection.

In a cell with N conversing subscribers, the total signal power received at the base station antenna is

$$P_N = N \cdot S_N + N_t \cdot W + I_o \tag{3.6}$$

From Equation 2.1, it follows that

$$S_N = \frac{N_t \cdot W + I_o}{\frac{W/(R \cdot \alpha)}{E_b/N_o} - (N-1)} \tag{3.7}$$

Since W, R, α, and E_b/N_o values do not change during the operation, the ratio $\frac{W/(R \cdot \alpha)}{E_b/N_o}$ is a constant value. Using F as a shorthand for this ratio, Equation 3.7, can be rewritten as

$$S_N = \frac{N_t \cdot W + I_o}{F + 1 - N} \tag{3.8}$$

Substituting Equation 3.8 in Equation 3.6, one gets

$$P_N = \frac{F+1}{F+1-N} \cdot (N_t \cdot W + I_o) \tag{3.9}$$

$$N_t \cdot W + I_o = P_N \cdot \frac{F+1-N}{F+1} \tag{3.10}$$

If one more call, new or handoff, is admitted, the total signal power received at the base station antenna will be

$$\begin{aligned} P_{N+1} &= (N+1) \cdot S_{N+1} + N_t \cdot W + I_o \\ &= (N_t \cdot W + I_o) \frac{F+1}{F-N} \\ &= P_N \cdot \frac{F+1-N}{F-N} \end{aligned} \tag{3.11}$$

The value P_{N+1} must be less than the total allowed interference level, TIM, in the cell for a handoff call to be granted a channel. The value P_{N+1} is called *CIM (Current Interference Margin)*.

In a cell where G channels have been reserved for handoff calls, a new call request is granted a channel if the total signal power that would be received at the base station antenna when the reserved channels are occupied, is below TIM. This value, called *HIM (Handoff Interference Margin)*, is equivalent to the total signal power

$$\begin{aligned} P_{N+G+1} &= (N+G+1)\cdot S_{N+G+1} + N_t \cdot W + I_o \\ &= (N_t \cdot W + I_o)\,\frac{F+1}{F-N-G} \\ &= P_N \cdot \frac{F+1-N}{F-N-G} \end{aligned}$$

3.5.1. Call Admissions with Adaptive Number of Reserved Channels

In this thesis, we extend the interference based channel reservation with adaptive number of guard channels. The admission scheme merged with the reservation scheme is described in the flowchart in Figure 3.4. The flowchart is extended from Figure 1 in [5] with the adaptive reservation mechanism.

The total signal power received at the base station antenna is measured periodically by the power strength measurer. The call admissions scheme is similar to the one described above, except that the number of guard channels is time varying, determined by the reservation scheme. Furthermore, the call admissions scheme is enriched with the algorithm of constructing the reservation area (see Section 3.3). The reservation scheme ensures that granting a reservation request does not violate the constraint that HIM should be below TIM. The number of reserved channels is re-calculated after every reservation request and handoff call request, either accepted or rejected. The updated value of number of reserved calls is used in the calculation of HIM in every iteration.

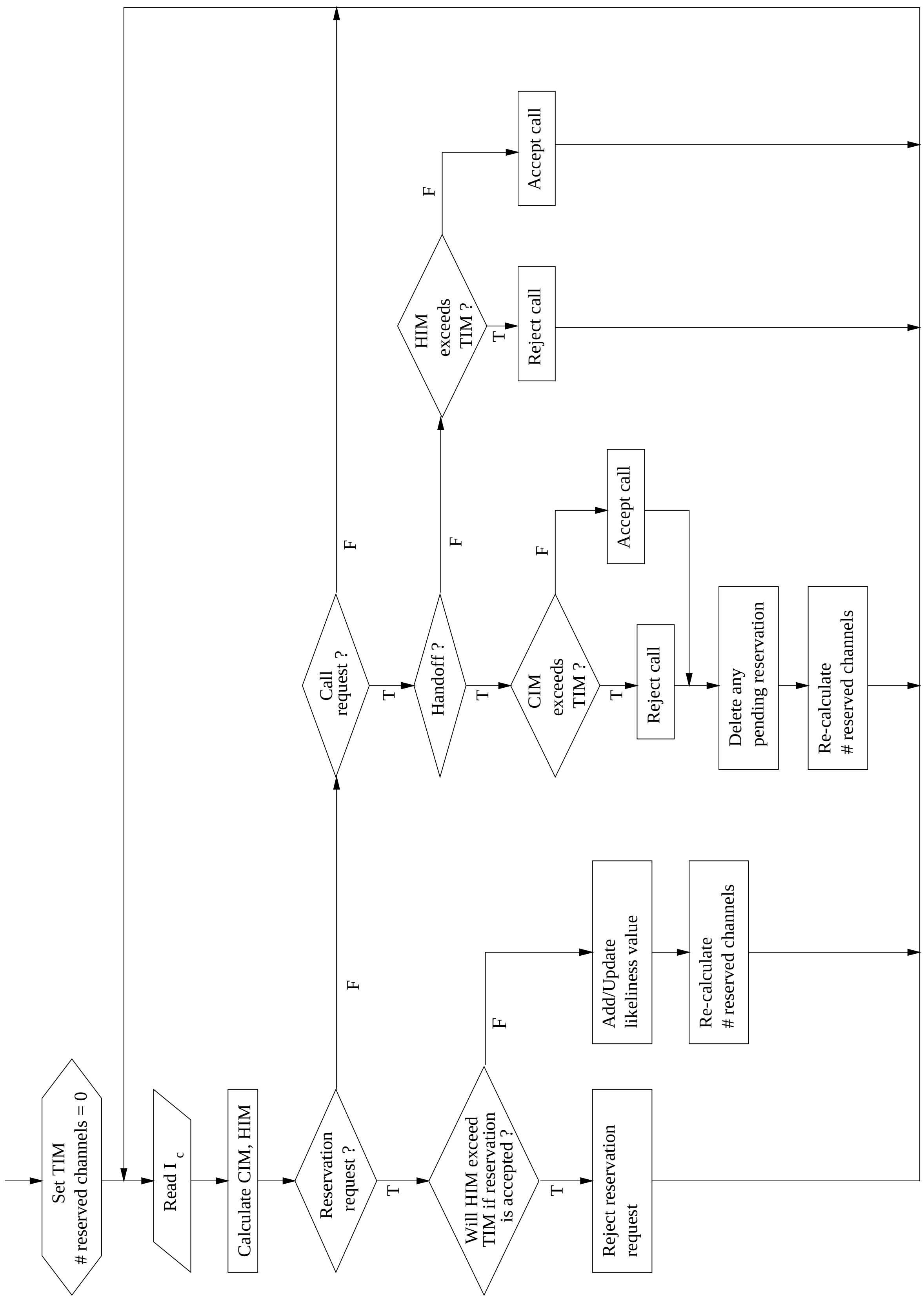


Figure 3.4. Call admissions with adaptive reservations

4. THE REALISTIC MOBILITY MODEL AND THE SIMULATOR

4.1. Existing Mobility Models in the Literature

Most of the work in the literature on mobile networks assumes random walk [48]-[55], Brownian motion [56], or cell change probability based on the side of the hexagon through which the subscriber leaves the cell [11], [57]. Although these models simplify the analysis, they rely on unrealistic assumptions, and the mobility patterns produced do not resemble the human behavior in real life. One of the most respected mobility models in the literature is the way point model. As an other alternative, in the random walk model, the mobility pattern of the each subscriber is defined relative to cells. The speed of the subscriber is selected uniformly from the given speed range, and the direction from the $[0, 2\pi]$ interval. Random walk is typically implemented with Markovian models where the subscriber moves to one of the neighboring cells, or stays in his current cell according to the given transition probabilities. In [58], Random Gauss-Markov model, which includes totally random walk and constant velocity models, is used. In [59], Su *et al.*, use way point mobility modeling for ad hoc networks. In the way point model, each subscriber chooses a direction and speed randomly, and moves in that direction at that speed for a while. Then, a new direction and speed is selected for the next step. However, in the way point model, the subscribers do not exhibit the real life features of the humans (See Section 4.2). In [60], Lam *et al.*, define traffic flow between cells as a function of the cell population. In [61], Markoulidakis *et al.*, have proposed a model with three levels: city area model, area zone model and street unit model, therefore the geographic area needs to be moulded into these three levels. In [62], Leung has modeled a highway with multiple entrances and exits as a deterministic fluid model. Different kinds of mobility models have been proposed in publications on ad hoc networks [63], [64]. However, since such networks are designed for disaster areas and military applications without any fixed cellular network their mobility patterns differ from those in a cellular system. In [65], Hong *et al.*, introduce *RPGM (Reference Point Group Mobility)*. However, their model applies only to ad hoc networks since they rely on the idea that there is a collaboration among the same team, and they partition the network into several groups, each with its own mobility model.

In addition to the theoretic work, simulators like OPNET [66], NS2 [67] and GloMo [68] also implement mobility models. However, OPNET has a very simple mobility model. Furthermore, it supports only AMPS as the air interface, not GSM or CDMA. NS2 does not support CDMA, either. GloMo has been developed for ad hoc systems and it is not suitable for cellular networks.

4.2. Motivation and Basic Idea

Our basic motivation in developing a novel mobility model instead of using the existing models in the literature was the key role of the mobility model in the performance evaluation of a proposed scheme. Unrealistic assumptions about the subscriber mobility patterns will leave the derived results open to question. Random mobility patterns cause the subscribers to generate new call and handoff requests in unrealistic fashions. Most of the existing mobility models rely on the autonomy of the subscribers in the decision making. Although the subscribers choose their directions independent of each other, the physical structures in the terrain, like roads, buildings, hills, impose similar constraints on all subscribers, forcing them to exhibit not similar, but related mobility patterns. This effect of the terrain on subscriber mobility causes different load on different parts of the service area.

Another motivation for a realistic mobility model was the adaptive channel reservation scheme proposed in Section 3. The proposed scheme relies on the fact that *human* subscribers make conscious moves towards a destination rather than arbitrarily changing direction. However, in most of the previous mobility models in the literature, the subscribers make unconscious moves. Such models make it impossible to estimate what may happen in the near future, resulting in pessimistic results. The results obtained by such mobility models represent what will happen when subscribers choose any direction at random, traveling over the buildings, trees, lakes, or driving at the speed of 120 km/h on a narrow street. However, they do not give much information about what will happen when the subscribers are forced to travel on the streets and respect the non-pass-through feature of physical structures like households. Basic features that should be supported by a realistic mobility model are discussed below:

- Since the mobiles are carried by human subscribers, they should exhibit autonomous and random mobility patterns while capturing the *moving-in-groups* behavior of the society [65]. In other words, the mobility patterns of the subscribers should be independent although an overall view gives the impression that people are moving back and forth between their offices and homes.
- The terrain should include hot spots [69]. Therefore, the mobiles must be distributed over the terrain in a non-uniform manner.
- The terrain should also include different structures like the houses, streets, highways, malls, lakes. The subscribers should respect the non-pass-through feature of some structures. For example, the subscribers should not drive over the houses.
- The transitions between these different structures should be well defined and the call patterns should also change accordingly. For example, the probability that a subscriber gets on the street should be defined, and the call pattern of the subscriber on the street should be different from the one at home.
- The mobility pattern should also include the calculation of the actual interference values. In outer cell interference calculations, assumptions like uniform distribution of the subscribers over the service area should be avoided.

Implementation of the autonomy of the subscribers is the crucial point of a mobility model. Each subscriber chooses his direction individually, as in real life. However, in real life, one can also observe that the direction of a subscriber is also dictated by the terrain. Although each subscriber makes his decision independent of the other subscribers, he cannot move around as he likes. If the street has a turn to the left, everyone on the street is supposed to turn to the left as long as they stay on the street. Thus, although the subscribers are autonomous, they drive or walk together on the streets and highways. This is called the *moving-in-groups* behavior of the society.

An autonomous subscriber updates his direction randomly so that the subscribers exhibit stochastic mobility patterns. However, determining the new direction independent of the current direction will result in a model where subscribers make unconscious moves, back and forth. A realistic mobility model should capture the *conscious traveling* feature of the subscribers where the subscribers tend to keep their directions towards a destination. However, this tendency is still subject to the *non-pass-through* feature of some structures in the terrain, as explained in the previous paragraph. The model should also force the subscribers to enter and leave the highways only at specific entrance and exit points. Furthermore, each subscriber exhibits an *inertial behavior* to preserve the type of structure he is on. A subscriber driving on a street is more likely to keep driving on the street than entering a household. However, the tendencies to switch from one type of structure to another should also be defined so that subscribers may prefer getting from the street to the avenue and vice versa. In addition to the mobility pattern, the call pattern of a subscriber is also effected by the structure on which the subscriber resides. Thus, the call pattern of the subscriber is altered when the mobile leaves home and starts driving.

The distribution of the subscribers over the service area is one of the crucial points in cellular systems. Unrealistic assumptions like uniform distribution of the subscribers results in even sharing of the load among the base stations which is contrary to the real life. The population density must differ throughout the service area denoting hot and blind spots like city centers and lakes.

Finally, the underlying air interface should also be considered since signal propagation is determined by the coordinates of the mobile. The mobility and call patterns, together with the population density effect the signal propagation. If CDMA technology is to be considered for the air interface, as in the third generation systems, the signal propagation model becomes more crucial. The approximation for the interference propagation in CDMA systems, given in [41], is commonly adopted in the literature. However, this approximation is based on the assumption that the mobiles are distributed evenly over the service area. If such an unrealistic assumption is to be avoided, one must also devise a means for interference propagation based on the actual location of the subscribers.

The path that a subscriber follows is implemented as the concatenation of line segments, called *steps*. As the steps get smaller, the path converges better to a curve at the expense of longer execution times. Longer steps may cause the subscribers to miss the corners at road crossings, resulting in subscribers always running on a straight line. Since the step size is determined by the multiplication of the step duration and speed, and the subscriber can update his speed and direction only at the beginning of a step, it will not be possible for a subscriber to turn a sharp corner. However, for reasonable step sizes, only the subscribers driving at high speeds on the highways will encounter such problems. Since there are no sharp corners on the highways, this does not constitute a problem. In fact, this is also the reason why in real life sharp corners are not placed on the highways. However, the step size may still be too large to take the curves on a road at some occasions. In such cases, when the subscriber cannot fit its step into the road, the step duration is decreased iteratively till the step fits into the road. After the subscriber takes the curve, the step duration is increased back to its specified value.

In this thesis, we propose a novel mobility model that captures the moving-in-groups, conscious traveling and inertial behaviors of the subscribers while respecting the non-pass-through features of the structures in the terrain. The model determines the mobility patterns of the subscribers according to a real topographic map, which contains various physical structures like buildings, streets, highways, sea. The mobility and call patterns of the subscribers are determined according to the locus of the subscriber in the terrain where the terrain is defined by real maps including hot and blind spots. The mobility and call patterns of a subscriber changes as he moves from one type of structure to another. Real life mobility patterns like walking, driving on the roads, entering and exiting highways, arriving and leaving home, even rowing across the Bosphorus can be implemented. Since we turn down the assumption that the mobiles are evenly distributed over the service area, we calculate the actual outer cell interferences. This mobility model is used to evaluate the performance of the adaptive channel reservation scheme described in Chapter 3.

4.3. Determining the Direction and Call Pattern of a Subscriber

Given a real map composed of different structures, the proposed model distributes autonomous subscribers over the service area, and generates stochastic mobility and call patterns for these subscribers. The number of different types of structures in the terrain is not fixed, and depends on how detailed the map is. The discriminating feature of the model is that the mobility and call pattern generations, together with the initial subscriber distribution is based on real maps. In this manner, initial subscriber distribution is realistic,

Figure 4.1. Map of Asian side of Istanbul

and subscribers in the same region of the terrain exhibit similar mobility and call patterns. For example, although the subscribers are autonomous, all subscribers on a road have to turn to the right if the road has a curve to the right. Furthermore, some structures in the terrain, may be set to be more likely places for the subscribers to turn their handsets on.

The initial distribution of the subscribers over the service area is determined according to the given map, and the specified effective weights (Table. 5.4) of the structures in the map. A weight matrix of the same size as the map is created with the elements initialized, starting from the lower-left corner, as a prefix-sum of the effective weights. Thus, the corresponding value in the weight matrix for a block with low effective weight is close to the values of the neighboring cells whereas it is much different for a block with high effective weight. The subscribers are distributed according to the effective weight matrix, favoring the blocks which differ from the surrounding blocks in terms of weight. Thus, it is possible to distribute mobiles such that some structures attract more subscribers than others. Once the initial distribution of the subscribers has been made this way, the subscribers are free to move over the service area causing variations in population over time.

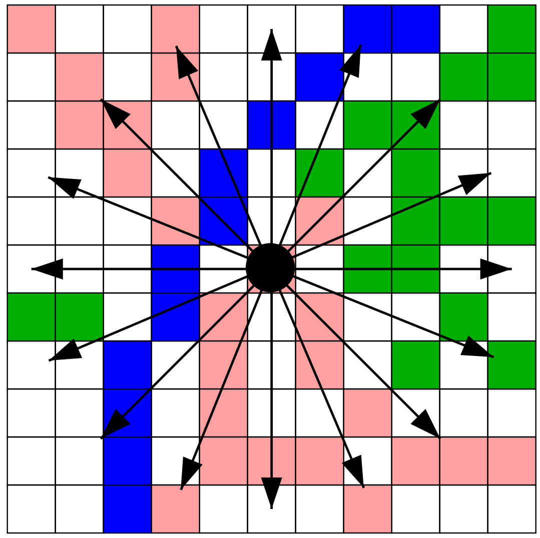


Figure 4.2. Finding the direction according to surrounding structures

Once a mobile terminal has been turned on, its direction is determined by the surrounding structures. This does not violate the fact that subscribers make autonomous decisions, since in the real life the movements of a human are also restricted by the environment. A subscriber decides whether he will switch to a different type of structure based on a matrix of structure switching probabilities. The change in the type of structure the subscriber is residing on implies a change in the mobility and call patterns of the subscriber. The new direction of a subscriber is found by sweeping 360^o in certain number of increments (Figure 4.2). The increase in the number of increments allows the subscriber to have a mobility pattern with finer granularity, but increases the execution time. It is a good idea to choose the number of increments as a prime number, and apply a shift to the directions so that no direction overlaps with the boundary of a cell. For each possible direction (shown with arrows in Figure 4.2), the probability of moving in that direction is calculated by multiplying the probability of switching from one type of structure to the other for all structures under the arrow. Thus, if there is a structure under the arrow to which the subscriber cannot move, the probability of moving in that direction will diminish so that the subscriber does not violate the non-pass-through feature of that structure. Once the probability of moving in each possible direction has been calculated, the probability for each direction is updated according to its proximity to the current direction. This update, together with the non-pass-through feature of the surrounding structures, implements the conscious traveling behavior of the subscriber. As long as the subscriber continues on same type of structure, there will not be significant changes in his speed or call pattern, showing the subscriber's inertia. Since all subscribers in the neighborhood will be subject to the same physical structures, they will have similar, but independent mobility patterns. Thus, the moving-in-groups feature of the society is implemented.

It is possible that the subscriber reaches the boundary of the terrain while moving in a given direction. Allowing the mobile to move out of the terrain will result in less subscribers in the service area, which may lead the simulation to end before the life time of all of the subscribers have expired. In order to prevent the number of subscribers from diminishing, we re-insert a subscriber who leaves the service area in a way similar to the initial subscriber distribution. Thus, we add a new subscriber to the system while another one leaves the system so that the total number of subscribers does not change.

Signal propagation in wireless systems requires special attention. Since the details of signal propagation is beyond the scope of this work, we simply employ the free space signal propagation [70] in our research. However, we still calculate the actual outer cell interference (Section 4.6) instead of employing the approximation introduced in [41] which is based on the assumptions we have turned down before.

In a stochastic system design, the implementation of the distributions and random number generators determines the validity of the system. We have used the CNCL package [71] for generating our distributions since it is a widely used and proven-to-be-correct library.

4.4. Finding the Controlling Base Station of the Mobile

We have assumed a hexagonal cellular structure as the cellular layout for our simulator for the sake of simplicity. Using the real cellular structure corresponding to the part of real map used would definitely provide better results. However, due to the difficulty of determining the real cellular layout, and the ease and speed of making calculations at the execution time have made such a regular layout more attractive. In our model, the controlling BS of the mobile is found according to the mobile coordinates (Figure 4.3). Finding the coordinates

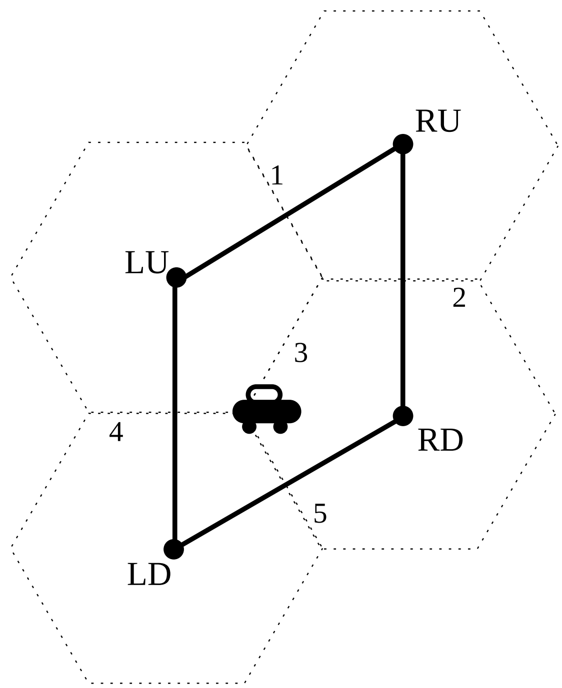


Figure 4.3. Finding the controlling base station of a mobile subscriber

of BS_{LD}[5] from the mobile coordinates is straight forward. The coordinates of BS_{LU}, BS_{RU} and BS_{RD} can be found from the coordinates of BS_{LD}. Thus, the mobile station is enclosed in the parallelogram shown in Figure 4.3, i.e., the controlling base station has to be one of those four BSs above. The controlling base station can be found by comparing the coordinates of the mobile against the edges 1, 2, 3, 4 and 5. The details of finding the controlling base station can be found in Appendix B.

4.5. Finding the Handoff Points

Since a regular hexagonal cellular structure is assumed, the handoff points are simply taken to be the intersection of the subscriber's step and the cell boundary. Finding whether a subscriber will encounter a handoff during his current step requires some geometric calculations. Since the hexagons are regular, finding the corners of the hexagonal cell and equations of the edges is straight forward. Thus, the problem of finding the handoff points is reduced to finding the intersection point of the subscriber's step and one of the edges of the cell. The reader should note that the subscriber's step may intersect the edges of more than one cells,

[5] BS_{XY} stands for the base station of cell XY, where XY takes the values LU, LD, RU and RD for the left up, left down, right up and right down cells respectively.

especially if the step is close to one of the corners of the cell.

4.6. Propagation of Outer Cell Interference

Since CDMA systems are interference sensitive, the accuracy in interference calculations is vital. Most of the work in the literature use the approximation provided by Gilhousen [41] in 1991. Gilhousen's approximation is easy to use, but depends on the assumption that the active subscribers are uniformly distributed over the service area. Since we turn down this assumption in our mobility model, and we know the exact coordinates of the subscribers, we also devise a method to calculate the actual outer cell interference with the free space signal propagation.

The signal of a mobile transmitting with the power A at a distance of κ will be received at power S at the base station [5]. The received signal power S is

$$S = A \cdot \kappa^{-\gamma} \cdot 10^{-\xi/10} \tag{4.1}$$

where ξ is the dB attenuation due to shadowing with mean zero, standard deviation σ. The typical values of σ and ξ in a cellular environment are [2.7-5.0] and 8 dB, respectively.

A user h at a distance κ_o from inner cell BS (Cell 0) and distance κ_m from the outer cell BS (cell k) produces the interference $I_u(h,k)$ at BS_o. The value of $I_u(h,k)$ can be found from the ratio

$$\frac{I_u\,(h,k)}{S} = \left(\frac{\kappa_m}{\kappa_o}\right)^{\gamma} \cdot 10^{(\xi_m - \xi_o)/10} \tag{4.2}$$

The aggregate interference at Cell 0 from all surrounding cells (set M of cells), I_o is

$$\frac{I_o}{S} = \sum_{k \in M} \sum_{h=1}^{n_k} \frac{I_u\,(h,k)}{S} \tag{4.3}$$

where n_k is the number of active users in Cell k.

4.7. Implementation Details

The implementation of all these features in a mobility model is a novel approach. Furthermore, the ability to support a stochastic mobility model with a real map adds power to the proposed model. The integration of the real map enables examining subscriber mobility on different service areas, like suburbs and rural areas.

The validation of the proposed model is a difficult task since it employs features based on subjective measures. Although it cannot substitute a formal proof, the best validation for such a model is visualization. We have implemented a graphical user interface (Figure 4.4) for the validation by using the EZD tool developed by DEC [72]. By the help of the graphical interface, we have validated that the proposed model provides the features claimed. The reason for choosing EZD is the support for EZD by the CNCL library[71]. However, EZD is not powerful enough to handle thousands of mobiles. Furthermore, fitting a very large map on the screen without zoom in/out features is not feasible. Since the implementation of such a powerful graphical interface is beyond the scope of this research, the authors have been contended with EZD.

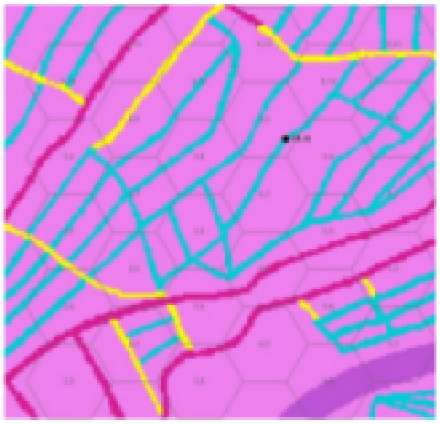


Figure 4.4. A screen capture from the graphical interface

4.7.1. The Class Hierarchy

The simulation software has been developed in object-oriented programming style using C++. Although numerous classes have been defined for the implementation, only three of them are significant from the point of view of this thesis document.

4.7.1.1. Network Class. This class acts as a container for all other classes. After initializing all parameters, the network class creates an instance of the base station class for each cell, and an instance of mobile class for each subscriber. After scheduling the turn on events of all mobiles, the network class waits till the end of the simulation. At the end of the simulation, all instances of the base station class are destroyed to force the statistics collection, and the simulation completes.

4.7.1.2. Base Station Class. This class manages the wireless resources for its assigned cell. All new call and handoff requests, together with the reservation requests are handled by this class. The base station class acts on behalf of the mobile class instances to construct the reservation area and manage the reservation request/update/delete operations.

4.7.1.3. Mobile Class. This class models the human subscriber. The basic function of the class is to implement the mobility and call patterns. The mobile class generates call requests to the base station at the time of the scheduled call start events. Since handoffs are determined according to mobile coordinates, the handoff requests are also generated by the mobile class.

4.7.2. Dependencies

The code has been developed using GNU C++ compiler (gcc 2.95.2 [73]). It can be compiled with any version above 2.8.0 on Linux and Solaris platforms. The statistics are stored in a GDBM database on Linux platform, and in text files on Solaris. Furthermore, the CNCL library [71] is required for compilation.

4.7.3. Incoming Call Scenarios

A cell may receive calls in two cases. A new call request occurs when the subscriber dials a phone number, or he is called. On the other hand, a handoff call request occurs when a subscriber moves from one cell to another during communication. Both of these call requests are handled by the call admission mechanism as follows.

Scenario 1: New Call Request. When the idle duration of a subscriber expires, the mobile class instance issues a new call request to the controlling base station class. The base station class compares its HIM value with TIM, and grants a channel for the mobile only if HIM is less than TIM; otherwise the call is rejected, resulting in a call block. If the call is accepted, the interference originating from the mobile is propagated, the reservation area for the mobile is constructed, and reservation requests are issued to all candidate cells. The interference and reservation information is updated by the controlling base station until the subscriber hangs up the mobile station or the mobile is handed over to a neighboring base station.

Scenario 2: Handoff Call Request. When an active subscriber moves to a new cell, a handoff request is issued. The “to-be” controlling BS checks if the CIM value is less than TIM; otherwise the handoff request is rejected, resulting in a call drop. If there is a pending reservation request that has been issued on behalf of this mobile previously, it is deleted in both cases. If the handoff request is accepted, the new controlling BS allocates a channel for the mobile, and performs the interference propagation and reservation area operations on behalf of the subscriber until the subscriber hangs up the mobile station or the mobile is handed over to a neighbor base station.

5. PERFORMANCE EVALUATION OF THE PROPOSED SCHEME

5.1. Experiment Methodology

We have evaluated the proposed reservation scheme with thorough tests. Two base problems have been defined for a typical cellular network. The effects of multiple factors on the system performance have been studied by varying the parameters of the base problem one by one to provide controlled experiments. The base problems are given in Subsections 5.1.1 and 5.1.2.

The results in Section 5.3 have been obtained by plotting the average of the results of numerous experiments with different seeds for each point in the graphs. Confidence intervals representing a confidence level of 95 per cent are shown in the graphs as errorbars at the data points. The number of seeds has been selected large enough to separate the confidence intervals except where it is necessary to emphasize the arbitrary behavior of the system. In most of the cases, 10 experiments with different seeds was enough to achieve a confidence level of 95 per cent. The results for the cells in the boundaries of the service area, i.e. *exterior cells*, have been excluded from the analysis to avoid incorrect conclusions, since such cells do not have all neighbors present, and they receive less outer cell interference than the interior cells. In the heavy load scenario, there is no limit on the simulation duration, i.e., the simulation ends when all mobiles have been turned off. In the light load case, the simulation duration of each test is half an hour, preceded with a five minute warm up period. All the mobile stations are turned on by the beginning of the warm up period to allow the system run with an actual load for five minutes, and the statistics are gathered following the expiration of the warm up period. When the simulation duration expires, no more statistics, except those for the already started calls, are gathered. To avoid the *cooling* of the system, i.e., the decrease in the load, while gathering statistics for the ongoing calls after the simulation period has expired, we continue generating new calls without taking them into account in the statistics.

5.1.1. Base Problem for Heavy Load

The base problem for the heavy load case represents a typical cellular network. A part of the real map in Figure 4.1 has been used as the underlying topology. The satellite image of the town of Kadıköy (a $6.4\,km$ x $6\,km$ area) has been digitized, and transformed into a map consisting of seven different types of physical structures to be used as the service area (Figure 5.1). We have also used handmade Manhattan-style networks (Figure 5.2). In both maps, the service area is represented with a resolution of $4\,m/block$, and is covered with a regular hexagonal cell layout of 0.6 km radius. The interference from each mobile station is propagated to 18 surrounding cells, which corresponds to a distance of two cells, with a γ factor of 4.0 as a typical value. An admitted call is assigned a channel at $9600\,bps$ data rate, and it is spread with a chip rate of $1228800\,chips/sec$ as specified in IS-95 [5], [74]. The ratio of bit energy to the noise power spectral density, E_b/N_o, is accepted to be 5.0, and the spectral density of thermal noise, N_t is taken to be $5.2908 \cdot 10^{-16}\ \frac{mW}{chips/sec}$. Also, a voice activation factor of 0.375 is assumed [41], [5], [6].

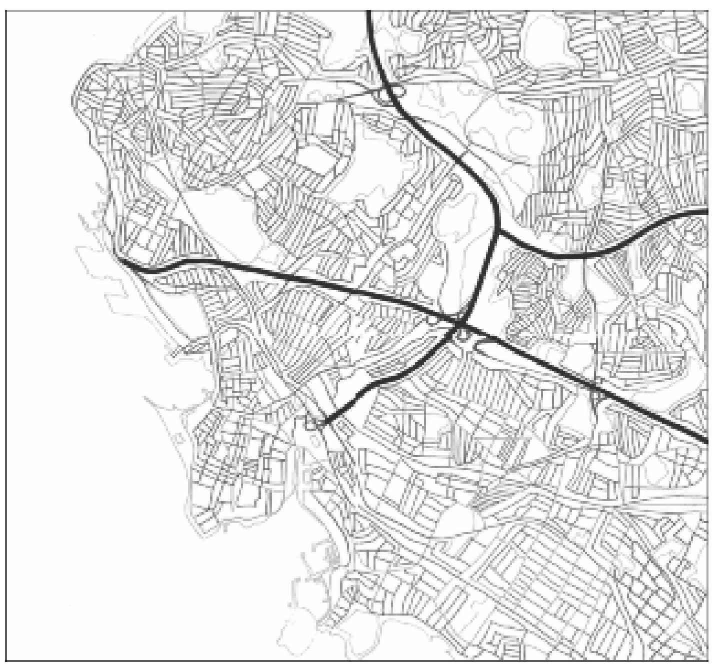


Figure 5.1. Real map after coloring

The parameters specific to the reservation area are as follows. Reservations are made by considering a reservation duration of 30 sec ahead. While estimating the change in di-

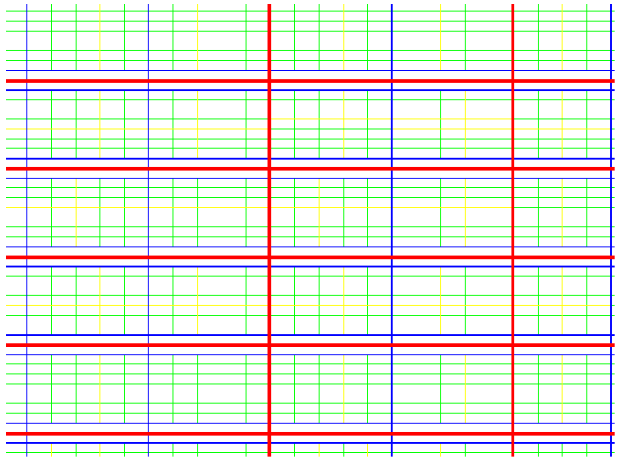


Figure 5.2. Pure Manhattan-style network

rection, past 10 directions changes are considered with a weight factor δ of 0.5. In the calculation of the likelihood value, the factors of distance and direction are 0.01 and 0.03, respectively. The values of these two factors have been determined with experimentation.

The corresponding system parameters are summarized in Table 5.1. The summary of the parameters specific to the simulator are given in Tables 5.2-5.4. The values for the idle duration and subscriber speed have been drawn from normal distributions with equal mean and variance. The block type change probabilities given in Table 5.3 are used in determining the direction of the subscribers. Since there are no subscribers in the empty regions, row 0 and column 0 have been excluded from Table 5.3. The parameters for the empty regions have been skipped for the same reason. Both the rows and the columns represent the values for the physical structures, empty regions (like sea, mountains and empty fields), households, streets, avenues, boulevards, connection roads and highways, respectively. The origin is specified as the row number and the destination as the column number. For example, the probability of moving from an avenue to a boulevard is given as 0.30, but from a boulevard to an avenue as 0.20, which means a subscriber on an avenue favors the boulevard, but not vice versa. Thus, the probability matrix is not symmetric across the diagonal. However, the sum of the values in a row should add up to one. The columns for which the sum of the values add up to a value less than one *yield* their subscribers to columns where the sum is over one.

Table 5.1. System parameters

Parameter	Value
Service area	6.4 km x 6 km (real map and pure Manhattan-style)
Cell radius	0.6 km
Number of cells in interference range	18
History length of mobile	10
History weight	0.5
Reservation duration	30 sec
Data rate	9600 bps
Chip rate	1228800 chips/sec
E_b/N_o	5
N_t	$5.2908 \cdot 10^{-16} \frac{mW}{chips/sec}$
α	0.375
γ	4.0
Likeliness factor of distance	0.01
Likeliness factor of direction	0.03

5.1.2. Base Problem for Light Load

This base problem represents a typical cellular network with a relatively lighter load. The maps of the heavy load case have been used for the service area with the addition of a Manhattan-style network with a hot spot (Figure 5.3). Except for the hot spot case, the service area is covered with a regular hexagonal cell layout of 1 km radius. The interference related parameters are the same as the parameters for the heavy load case.

The parameters specific to the reservation area are as follows. Reservations are made for a reservation duration of 30 sec ahead. While estimating the change in direction, past 10 direction changes are considered with a weight factor δ of 0.5. In the calculation of the likelihood value, the factors of distance and direction are 0.3 and 0.6, respectively.

Table 5.2. Simulation parameters

Parameter	Value
Steps/reservation request	3
Map granularity	4 m/step
Step duration	5 sec/step
Number of directions	17
Direction change coefficient	8
Number of block types	7
Block type change probabilities	See Table 5.3
Subscriber call and mobility patterns	See Table 5.4

Table 5.3. Block type change probabilities

	1	2	3	4	5	6
1	0.60	0.30	0.10	0.00	0.00	0.00
2	0.15	0.50	0.30	0.05	0.00	0.00
3	0.05	0.15	0.45	0.30	0.05	0.00
4	0.00	0.03	0.20	0.47	0.30	0.00
5	0.00	0.00	0.05	0.20	0.20	0.55
6	0.00	0.00	0.00	0.00	0.10	0.90

Table 5.4. Subscriber call and mobility patterns with respect to the type of block for the heavy load case

Block type	Pattern	Type of distribution	Parameter(s) of distribution
0 Empty region	-	-	-
1 Households	Idle duration	Normal	(1 min, 1 min)
	Call duration	Exponential	600 sec
	Speed	Normal	(5 km/h, 5 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	5
2 Streets	Idle duration	Normal	(2 min, 2 min)
	Call duration	Exponential	300 sec
	Speed	Normal	(30 km/h, 30 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	5
3 Avenues	Idle duration	Normal	(3 min, 3 min)
	Call duration	Exponential	300 sec
	Speed	Normal	(60 km/h, 60 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	15
4 Boulevards	Idle duration	Normal	(5 min, 5 min)
	Call duration	Exponential	360 sec
	Speed	Normal	(80 km/h, 80 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	40
5 Connection roads	Idle duration	Normal	(5 min, 5 min)
	Call duration	Exponential	480 sec
	Speed	Normal	(110 km/h, 110 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	80
6 Highways	Idle duration	Normal	(5 min, 5 min)
	Call duration	Exponential	480 sec
	Speed	Normal	(140 km/h, 140 km/h)
	Life time	Normal	(300 min, 300 min)
	Effective weight	-	150

The same parameters apply for the hot spot case, with the following exceptions: a cell radius of 0.2 km representing smaller cells in downtown areas on a 3.28 km x 3.36 km map, a data rate of 19200 bps representing channels to support wireless applications, a reservation duration of 45 sec, and likelihood factors as $(0.2, 0.4)$.

The increase in the data rate affects only the system capacity in terms of the number of channels available. This change in system capacity can be better understood by examining Figure 2.1 again. The increase in data rate R causes the signal power S to increase. The increase in S, in turn, causes the spectral density of the received signals at the base station to increase, resulting in a smaller number of subscriber signals to maintain the maximum allowed interference level. Thus, the capacity per cell decreases from approximately 64 channels to 32 channels as the data rate increases from 9600 bps to 19200 bps.

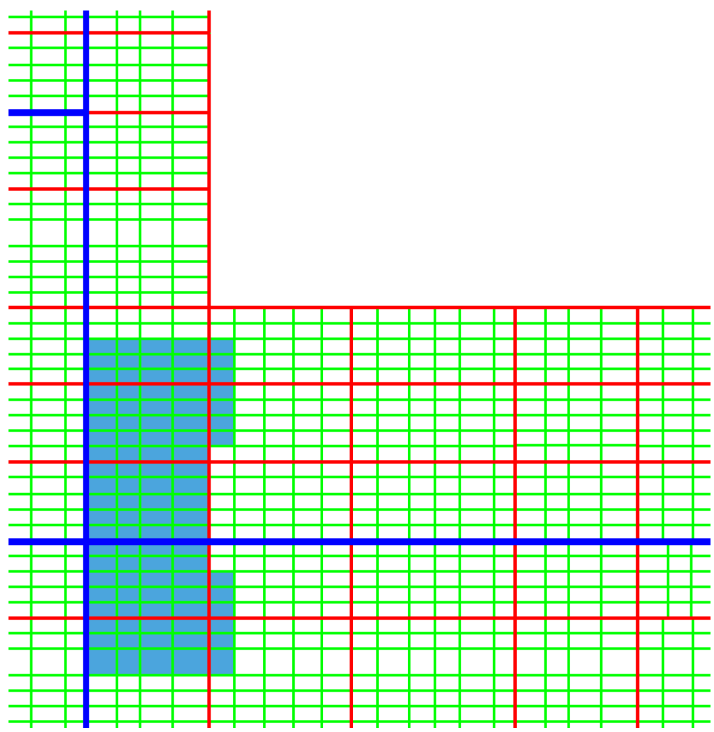


Figure 5.3. Manhattan-style network with hot spot

The corresponding system parameters are summarized in Table 5.5. The summary of the parameters specific to the simulator are given in Tables 5.6-5.8. The block type change probabilities given in Table 5.7 are used in determining the direction of the subscribers.

Table 5.5. System parameters

Parameter	Value
Service area	6.4 km x 6 km (real map and pure Manhattan-style network) 3.28 km x 3.36 km (Manhattan-style network with hot spot)
Cell radius	1 km (real map and pure Manhattan-style network) 0.2 km (Manhattan-style network with hot spot)
Number of cells in interference range	18
History length of mobile	10
History weight	0.5
Reservation duration	30 sec (real map and pure Manhattan-style network) 45 sec (Manhattan-style network with hot spot)
Data rate	9600 bps (real map and pure Manhattan-style network) 19200 bps (Manhattan-style network with hot spot)
Chip rate	1228800 chips/sec
E_b/N_o	5
N_t	$5.2908 \cdot 10^{-16} \frac{mW}{chips/sec}$
α	0.375
γ	4.0
Likeliness factor of distance	0.3 (real map and pure Manhattan-style network) 0.2 (Manhattan-style network with hot spot)
Likeliness factor of direction	0.6 (real map and pure Manhattan-style network) 0.4 (Manhattan-style network with hot spot)

Table 5.6. Simulation parameters

Parameter	Value
Steps/reservation request	5
Simulation duration	30 min
Warm up period	5 min
Map granularity	4 m/step
Step duration	5 sec/step
Number of directions	17
Direction change coefficient	8
Number of block types	7
Block type change probabilities	See Table 5.7
Subscriber call and mobility patterns	See Table 5.8

Table 5.7. Block type change probabilities

	1	2	3	4	5	6
1	0.60	0.30	0.10	0.00	0.00	0.00
2	0.15	0.50	0.30	0.05	0.00	0.00
3	0.05	0.15	0.45	0.30	0.05	0.00
4	0.00	0.03	0.20	0.47	0.30	0.00
5	0.00	0.00	0.05	0.20	0.20	0.55
6	0.00	0.00	0.00	0.00	0.10	0.90

Table 5.8. Subscriber call and mobility patterns with respect to the type of block for the light load case

Block type	Pattern	Type of distribution	Parameter(s) of distribution
0 Empty	-	-	-
1 Households	Idle duration	Normal	(60 min, 60 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(1 km/h, 1 km/h)
	Effective weight	-	1
2 Streets	Idle duration	Normal	(30 min, 30 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(10 km/h, 10 km/h)
	Effective weight	-	100
3 Avenues	Idle duration	Normal	(30 min, 30 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(35 km/h, 35 km/h)
	Effective weight	-	100
4 Boulevards	Idle duration	Normal	(30 min, 30 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(50 km/h, 50 km/h)
	Effective weight	-	100
5 Connection roads	Idle duration	Normal	(30 min, 30 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(70 km/h, 70 km/h)
	Effective weight	-	150
6 Highways	Idle duration	Normal	(20 min, 20 min)
	Call duration	Exponential	60 sec
	Speed	Normal	(90 km/h, 90 km/h)
	Effective weight	-	250

5.2. Computation and Communication Complexity

It is obvious that the proposed method brings a burden on the base stations and fixed links between the base stations in terms of computation and communication complexity, respectively. As stated in Section 3.2, each base station is responsible for constructing and maintaining the reservation area of all active mobiles under its control. Furthermore, each base station responds to the incoming reservation requests from neighboring base stations.

Processing the reservation requests is not a complex task since all it requires is to check whether adding the signal power of one more subscriber causes the total interference received to exceed the maximum allowed interference margin. In other words, processing a reservation request implies an addition and a comparison. On other hand, constructing the reservation area is more complex since it requires establishing the elliptical region and finding the set of candidate cells that intersect the reservation area. The details of this process has been given in Sections 3.3-3.4. Maintaining the reservation area during the call has the same complexity as the construction of the area.

The complexity of the process of establishing the elliptical region can be obtained from Equations 3.1-3.4. The complexity is $O\left(T \cdot N\right)$, where T is the length of history considered for the estimating the change in direction and N is the number of active subscribers, typically limited around 64. The value of T has been selected as 10 in the experiments. The complexity of establishing the set of candidate cells is limited by the size of the reservation area. The largest set of candidate cells is established when the elliptical reservation area is distorted to a circle. The number of candidate cells in this case is limited from above by

$$\left\lceil \pi \cdot \left(\frac{d}{2 \cdot r} + 1 \right)^2 \right\rceil \qquad (5.1)$$

where

d is the distance subscriber can travel with his current speed in the reservation duration,

r is the cell radius.

The largest set of candidate cells in the experiments is formed when cell radius is as low as 250 m with a reservation duration of 30 sec. The size of the candidate set of a very fast subscriber moving at a speed of 120 km/h speed (which is not practical in such a microcell environment) is 13.

For each candidate cell the likelihood calculation (Equation 3.5) is made with complexity $O(1)$. Since the construction of the reservation area is composed of the establishment of the elliptical region and the candidate set, the computation complexity per base station of the proposed scheme is

$$O\left(T \cdot N + \frac{d}{r}\right) \tag{5.2}$$

The burden of communication overhead of the proposed scheme results from the reservation requests between the base stations. For each reservation request, a small message containing the source base station id, mobile station id and the likeliness value is sent to the candidate base station. Therefore, the communication overhead is defined by the number of base stations, the number of active subscribers in each cell and the size of the candidate cell for each active subscriber. The communication complexity has an upper bound of

$$O\left(M \cdot N \cdot \frac{d}{r}\right) \tag{5.3}$$

where M is the number of cells in the service area. For the case specified above, the value of M and N are 42 and 32, respectively.

5.3. Experiments Performed

We have evaluated the performance of the proposed call admission scheme by considering its effect on call dropping and call blocking. In addition to considering the CDP and CBP values, we have also devised new metrics, called *dropping ratio* and *blocking ratio*. Besides analyzing the performance of the overall network, we have also analyzed the effect of the proposed scheme on individual cells. In the literature, CDP is defined as the ratio of dropped calls to the number of successfully started calls. However, according to this definition, CDP can be considered only for the overall network. Since a call that has been dropped in a specific cell may have been started in any cell, including the cell under inspection, CDP in this specific cell cannot be calculated by taking the ratio of the number of calls dropped and started in this cell. This conclusion is straight forward from the fact that the dropped call is not necessarily one of the calls started in this cell. Therefore, we have defined the dropping ratio metric as the ratio of the number of dropped calls in the current cell to the number of handoff requests to the cell. The blocking ratio is, similar to CBP, the ratio of blocked calls in the current cell to the number of new call attempts in the cell. We have also analyzed *GoS (Grade of Service)* for the overall network as a combined metric of CDP and CBP.

5.3.1. Experiments for the Heavy Load Case

5.3.1.1. Effect of Making Reservations. The effect of making reservations in the heavy load case is studied for two different scenarios.

Scenario 1 (Map based model). In the heavy load case, we have tested the effect of the proposed scheme against the plain scheme without any guard channels. The simulations for both schemes have been done by using the proposed mobility model with a real map of $38\,km^2$ (part of Figure 4.1) as the underlying topology. The results obtained for these two schemes are plotted in Figure 5.4. The proposed scheme provide drastic cuts in CDP at the expense of an increase in CBP. This is of course expected, since handoff calls have more chance to find a free channel while new call attempts may be blocked since handoff calls have privilege over new calls.

Scenario 2 (Way point model). The effect of reservations have been tested also with the way point mobility model. It is apparent from Figure 5.5 that the proposed model again performs better than the plain scheme for the cases studied. By comparing Figure 5.5 with Figure 5.4, one can observe that the effect of the proposed scheme is not highlighted when the way point mobility model is used. This is not surprising since the subscribers make

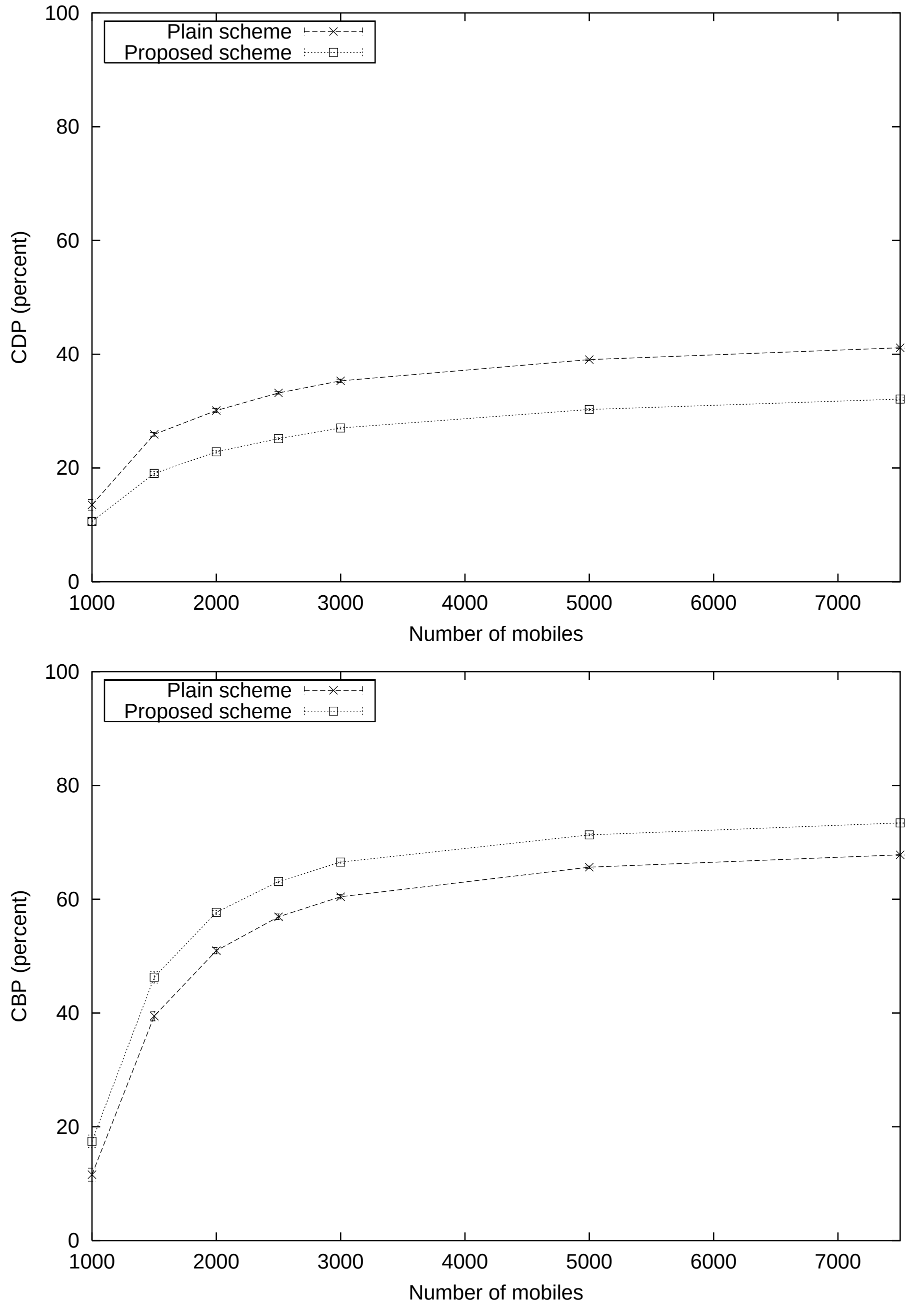


Figure 5.4. Effect of making reservations on a real map

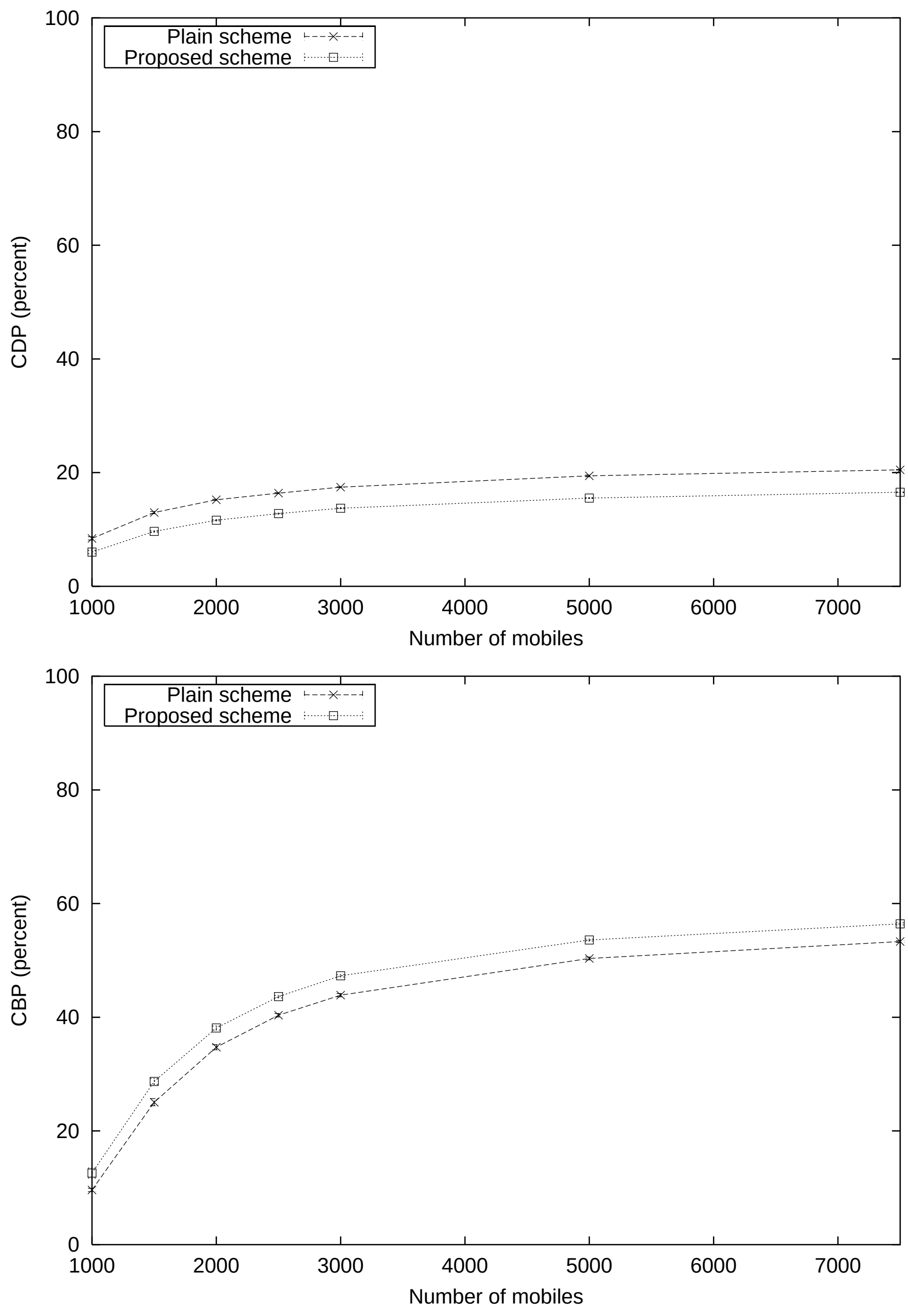


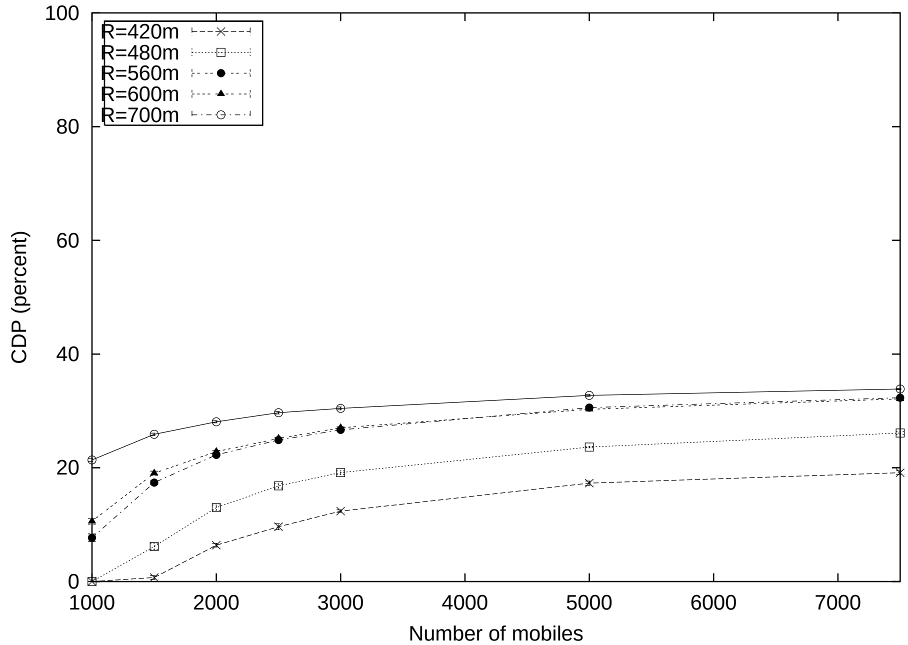
Figure 5.5. Effect of making reservations with the way point mobility model

random moves in the way point model. Therefore, it is highly probable that the subscriber moves out of the reservation area. This is one of the main reasons for justifying the use of a realistic mobility model.

5.3.1.2. Effect of Cell Radius. We have analyzed the effect of the cell radius, and sketched the results in Figure 5.6. Both CDP and CBP increase with increasing cell radius. Although increase in cell radius implies longer sojourn times, and therefore, less handoffs, CDP and CBP increase because there are more subscribers in the same cell. The effect of increase in cell radius is more significant in smaller cells.

5.3.1.3. Effect of Map Type. The effect of the map type on system performance is analyzed in Figure 5.7. It is visible from the graphs that the change in the type of map does not cause a significant change in the trend of the behavior of the system, but there is a considerable difference in the values of both CDP and CBP with respect to the real map. This is mainly because of the fact that in the perfect Manhattan-style network, the roads are straight lines and the corners are very sharp at 90^o. This causes the subscribers to move in the same direction for a long time. Thus, the reservation area becomes very narrow. The subscribers also make very sharp turns at the corners, suddenly moving out of the narrow reservation area. The reason for the increase in blocking can be explained by the distance between the avenues, which seems to be closer than the real map. The reader should note that, the Manhattan-style network has been created simply by the repetition of a small segment. The service area in the Manhattan-style network is equal to the available service area in the real map, i.e., what remains after empty regions are extracted.

5.3.1.4. Effect of Mobility Pattern. The effect of the mobility pattern has been analyzed on both the plain scheme (Figure 5.8) and the proposed scheme (Figure 5.9). Since the subscribers are accumulated at specific parts of the terrain with the map based mobility model, its CBP is well above that for the way point model. The reason for higher CDP in the way point case can be explained by considering the mobility patterns of the subscribers as follows. In the way point model, all subscribers exhibit similar mobility patterns. However, in the map based model, subscribers at home almost never encounter handoffs. In other words,



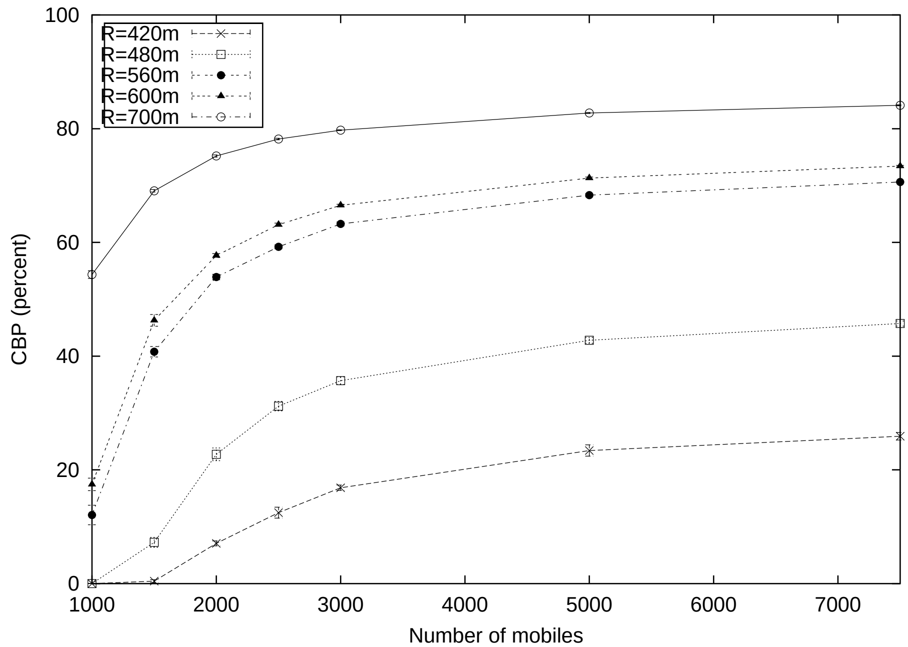


Figure 5.6. Effect of cell radius for the proposed scheme

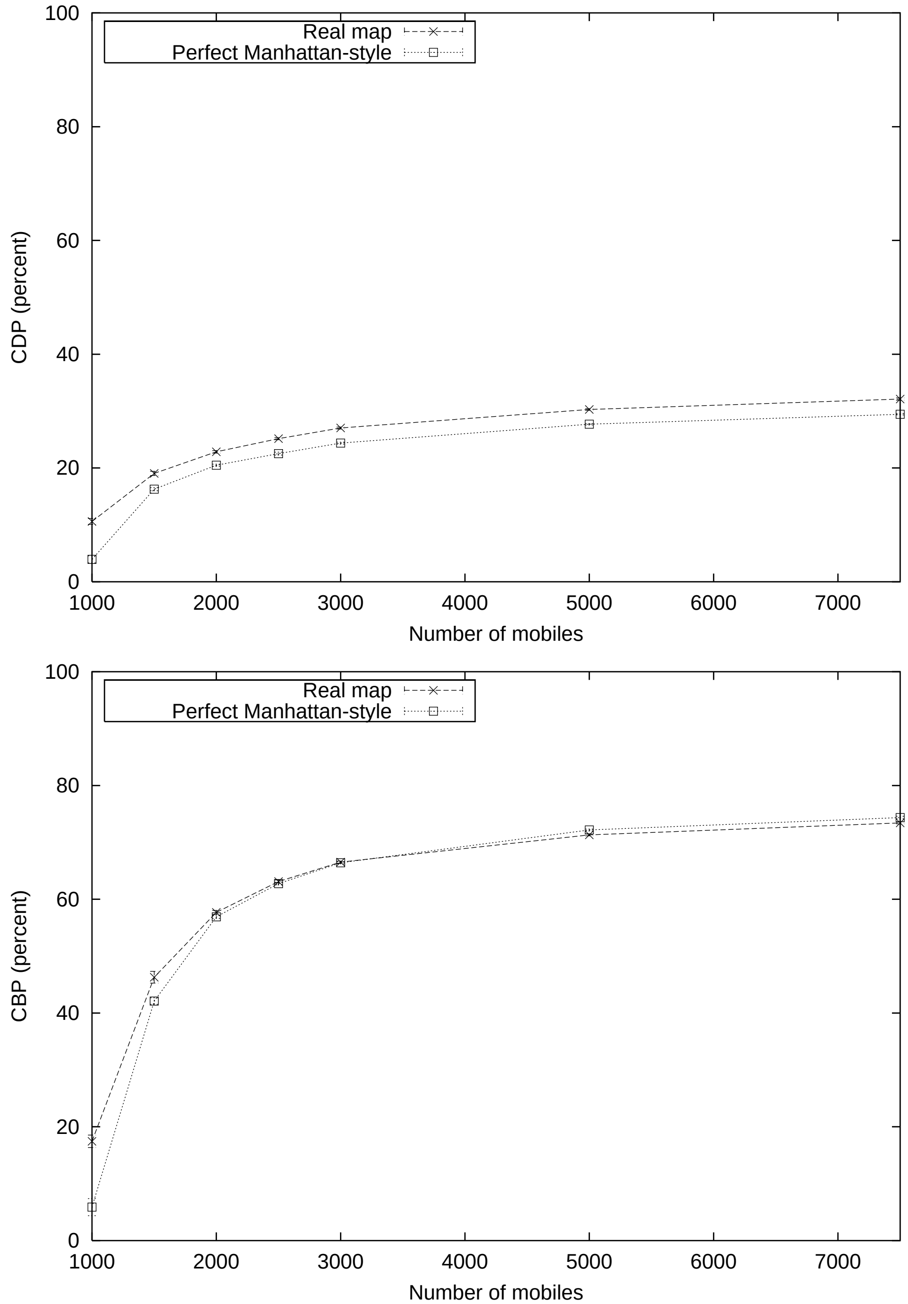


Figure 5.7. Effect of map type for the proposed scheme

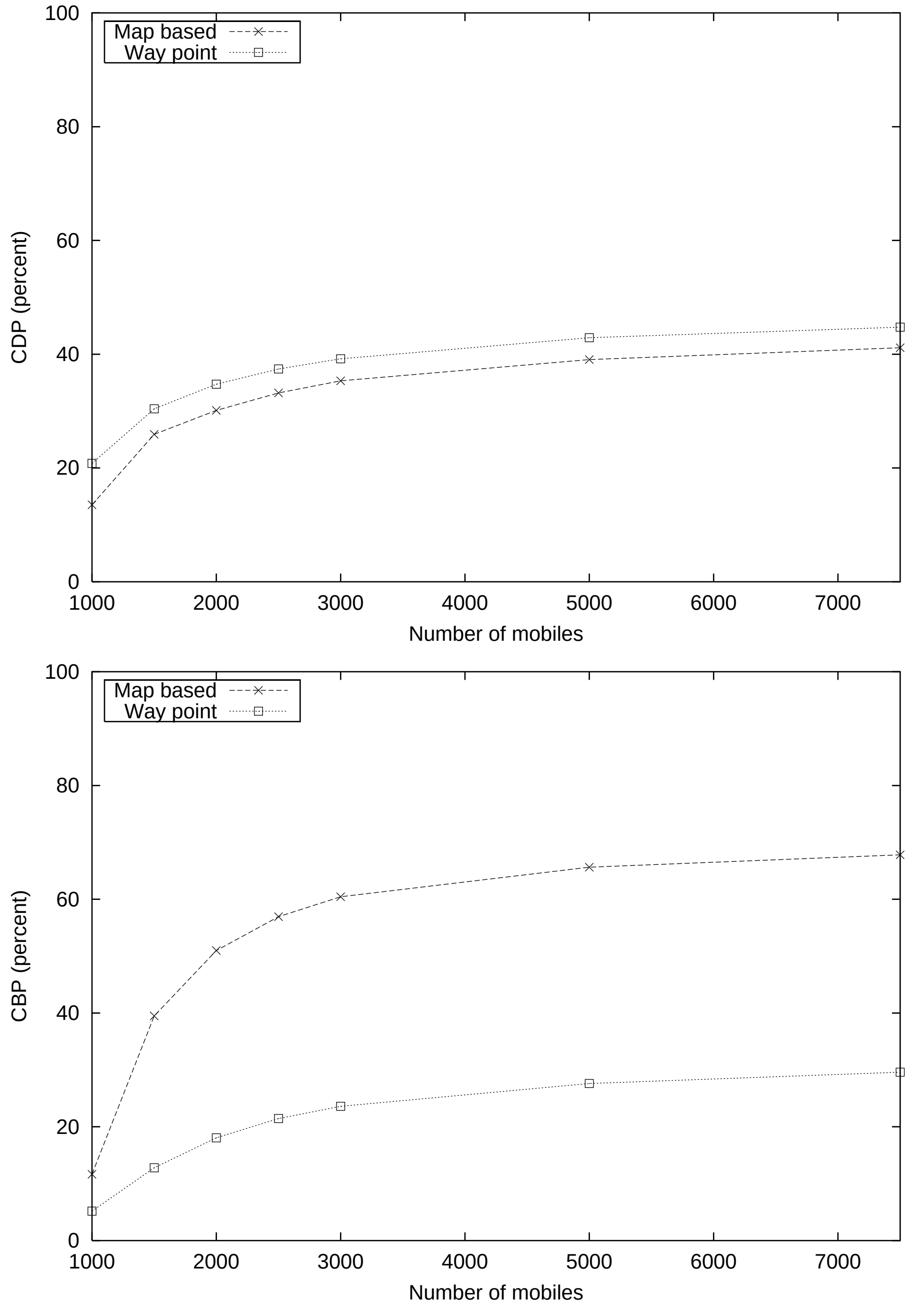


Figure 5.8. Effect of mobility pattern for the plain scheme

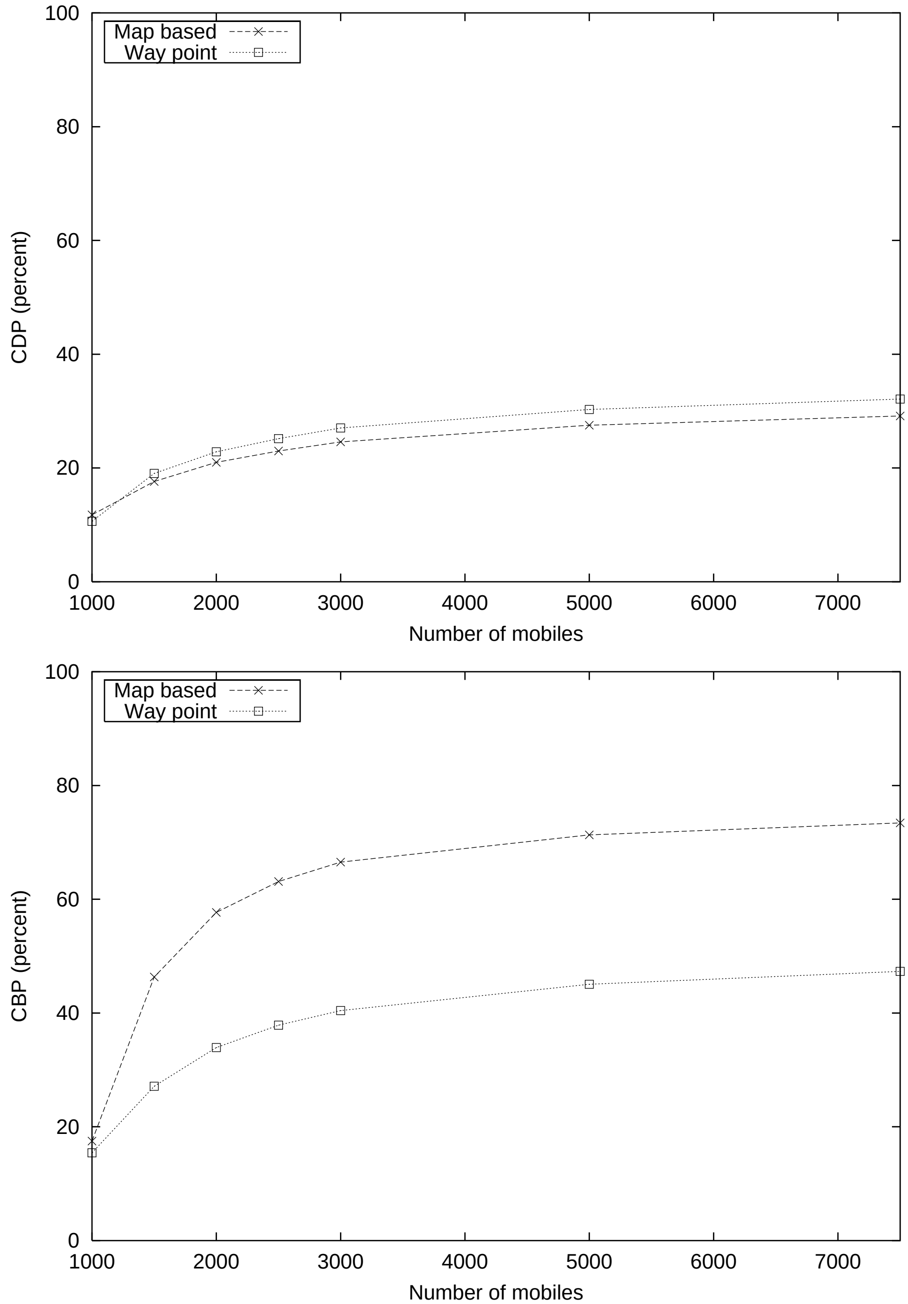


Figure 5.9. Effect of mobility pattern for the proposed scheme

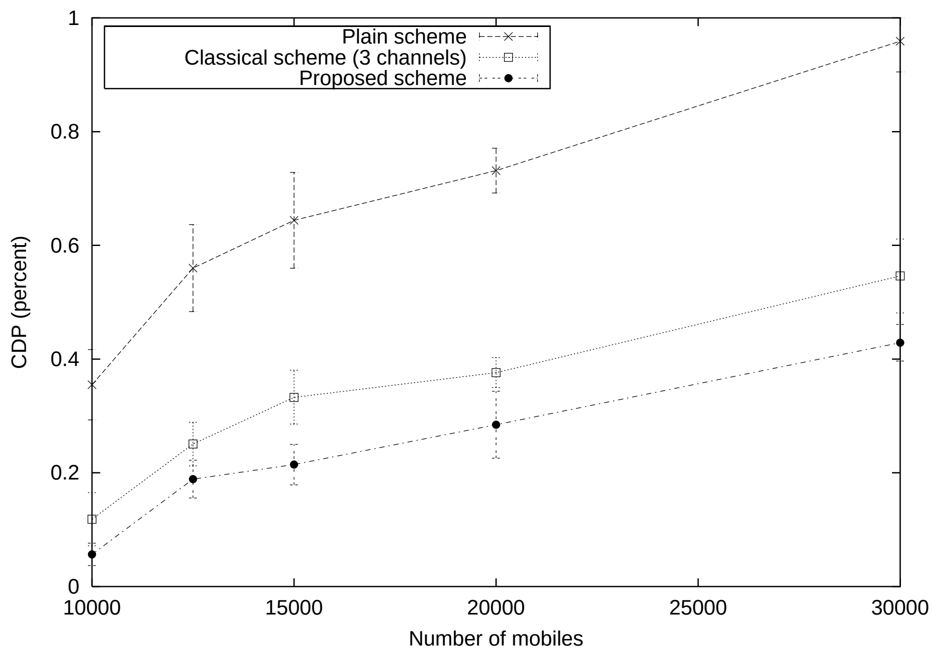
the number of subscribers subject to handoffs is higher in the way point model, although the average speeds for both models is the same. Therefore, since fewer subscribers may be moving at higher speeds in the map based model, the number of handoff attempts is less than the number of handoffs created by all subscribers in the way point model. The reader should also note that the proposed scheme decreases the difference between the CDP values of way point and map based models.

5.3.2. Experiments for the Light Load Case

5.3.2.1. Effect of Making Reservations. The effect of making reservations in the light load case is studied for three different scenarios.

Scenario 1 (Map based model with the real map). We tested the effect of the proposed scheme against the classical guard channel scheme and the plain system without any guard channels. It has been observed that in the literature, two or three channels are being used as guard channels [5], [6]. Therefore, three guard channels have been allocated in each cell for the classical guard channel system. The simulations for all three schemes have been done by using the proposed mobility model with a real map of $38\,km^2$ (part of Figure 4.1) as the underlying topology. The results obtained for these three schemes are plotted in Figure 5.10. Both the classical guard channel scheme and the proposed scheme provide drastic cuts in CDP. This is, of course expected, since handoff calls have more chance to find a free channel. However, since the classical scheme allocates a constant number of guard channels, the dropping probability of a handoff call to a cell, which receives many handoff calls, in the classical scheme is higher than that in the proposed scheme. Furthermore, the proposed scheme performs better than the classical without any increase in cost, i.e., without any increase in CBP.

Scenario 2 (Way point model). The effect of reservations was tested also with the way point mobility model. From Figure 5.11, one can observe that with the way point model, the plain scheme cannot be distinguished from the classical guard channel scheme. The



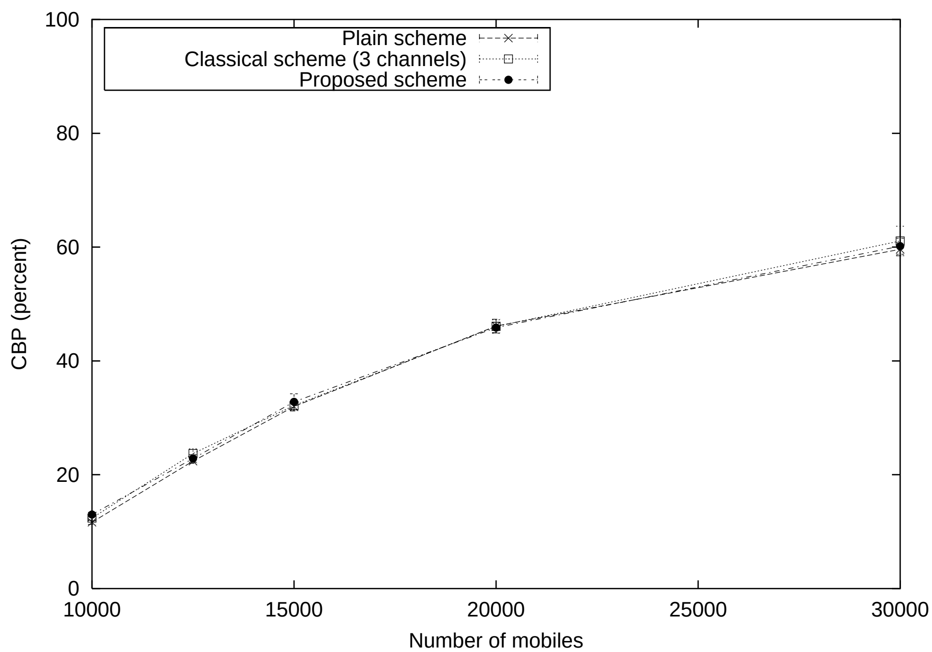


Figure 5.10. Effect of making reservations on a real map

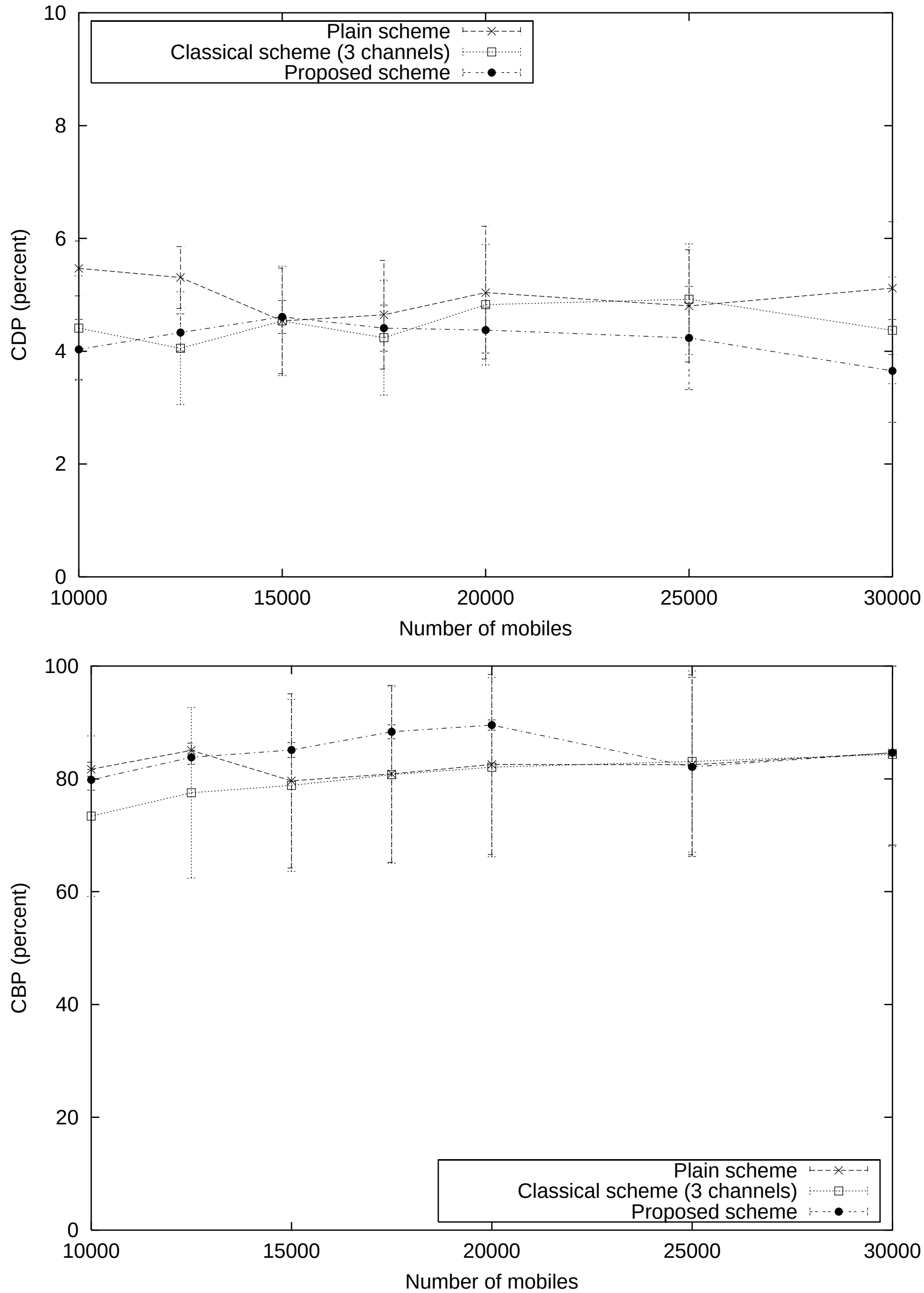


Figure 5.11. Effect of making reservations with the way point model

proposed scheme performs slightly better than both of the other schemes, but the difference is not significant. However, we should note that the proposed scheme is more stable than the other two schemes in terms of load, i.e., the number of subscribers. The number of seeds used for the experiments in Figures 5.10 and 5.11 are the same. The high variation in Figure 5.11 represents the unstable nature of the way point model. The reason for the low dropping probabilities, with respect to the high blocking rates is that the mean speed of the mobiles in the way point model is only $35\,km/hr$.

Scenario 3 (Map based model with Manhattan-style network including hot spots). In order to prove the proposed model performs better than the classical guard channel scheme, we tried to find out the number of guard channels that should be used to catch up with the proposed scheme. From Figure 5.12, it can be observed that six guard channels results in higher CDP and almost equivalent CBP. Using seven guard channels instead gives higher CDP, and also higher CBP. Therefore, the optimum number for the classical scheme is six guard channels, and that cannot cope with the proposed scheme either. The reader should also note that six guard channels in approximately 32 total number of channels corresponds to allocating 20 per cent of the available channels for handoff calls, which is not very common practice. The confidence intervals are very narrow, and therefore almost invisible. The plain scheme has not been plotted in Figure 5.12 so that the difference between the other schemes do not become invisible in the graphs. The CDP and CBP values for the plain scheme are over 12 per cent and 49 per cent, respectively, for the case of $90,000$ mobile stations.

We have also compared these three systems in terms of the maximum dropping and blocking ratios (Figure 5.13), and GoS (Figure 5.14). We have obeyed the GoS definition in [5], and used it as

$$GoS = 10 \cdot CDP + CBP \tag{5.4}$$

The maximum CDP and CBP values represent the worst case behavior of the system over the service area. The proposed scheme performs the same as the classical scheme with

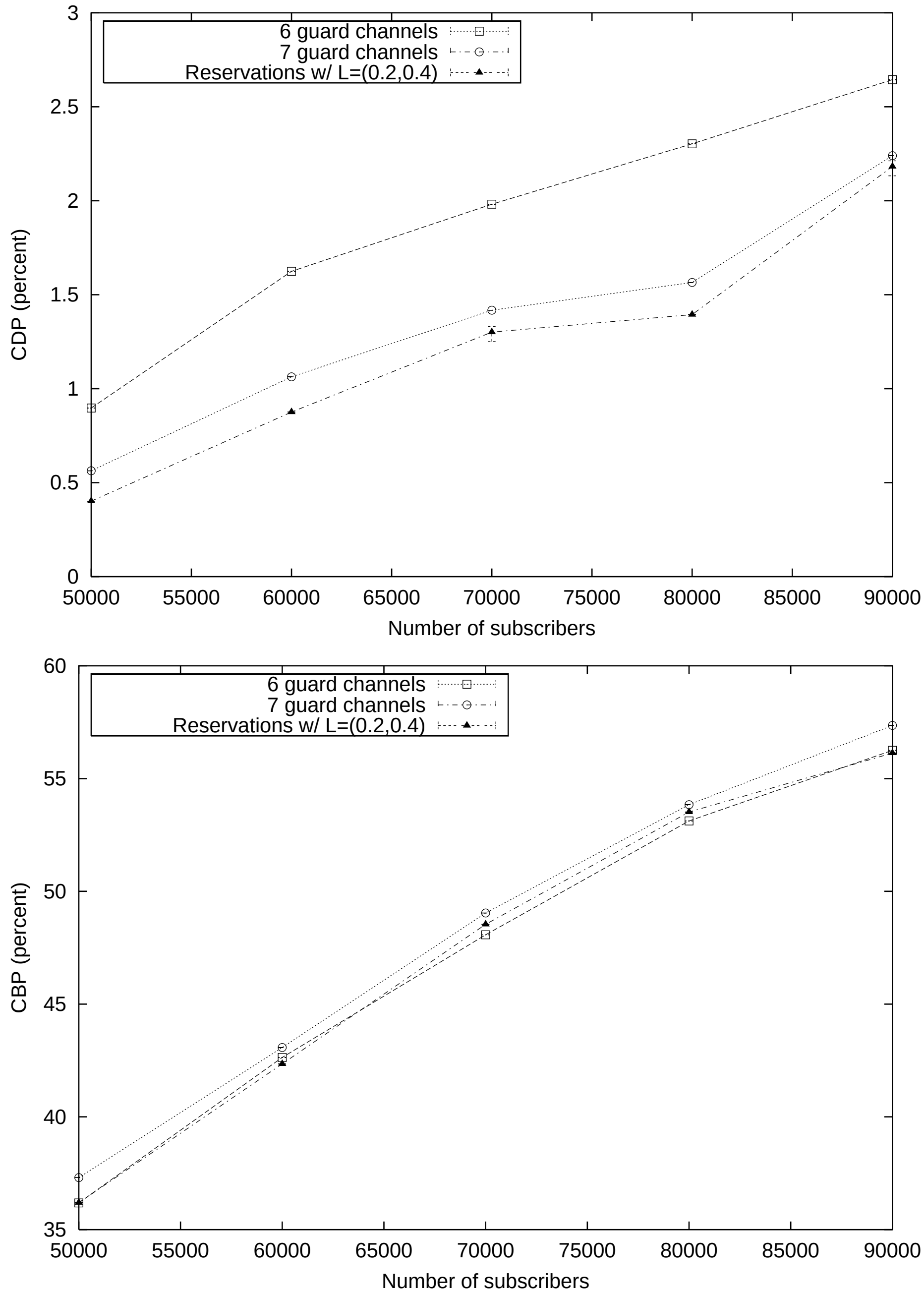


Figure 5.12. Effect of making reservations on a Manhattan-style network with hot spots

seven guard channels in terms of CDP while maintaining a lower CBP, i.e., at a lower cost. The reader should note that the definition for GoS above is different from the generally used definition based on CDP [75].

5.3.2.2. Effect of Reservation Duration. We analyzed the effect of reservation duration on the system performance and sketched the results in Figure 5.15. It is apparent from the graphs that a reservation duration of $45\,sec$ performs better than the others. The reason for CDP is straight forward, since we make reservations for a longer period in the near future, which results in larger reservation areas. The unstable behavior in short reservation durations of $5\,sec$ and $10\,sec$ can be explained by considering the simulation parameters "step duration" and "steps/reservation request". Of these two parameters, the former denotes how often the subscriber updates his speed and direction, and the latter denotes in how many steps the reservation request (and the associated likelihood value) is updated. Thus, the reservation request is updated once in every $25\,sec$. Therefore, the reservation durations shorter than $25\,sec$ build reservation areas which cover a future period shorter than the reservation update interval. In other words, some part of the subscriber's journey is not covered by the reservation area. This is not the case for the reservation durations of $30\,sec$ and $45\,sec$, therefore the system is in a stable state for these reservation durations. The reader should note that the reservation duration specified in the base problem is $30\,sec$, not $45\,sec$. The reason for almost no change in CBP is that the number of reserved channels does not change very much with the change in reservation duration, and therefore, among the many calls blocked, the change is not apparent. On the other hand, since CDP is very low, the effect of the slight change in the number of guard channels is more effective.

5.3.2.3. Effect of Likelihood Factors. The effect of likelihood factors are presented in Figure 5.16. The larger the factors grow, the lower the CDP is. This is not surprising since the likelihood value specified in the reservation requests gets larger with increasing factors. Thus, more channels are reserved in the candidate cells. As a consequence of this, CBP gets higher as the factors grow. The likelihood factors should be regarded as a tuning-knob to adjust the system to the preferred CDP and CBP values.

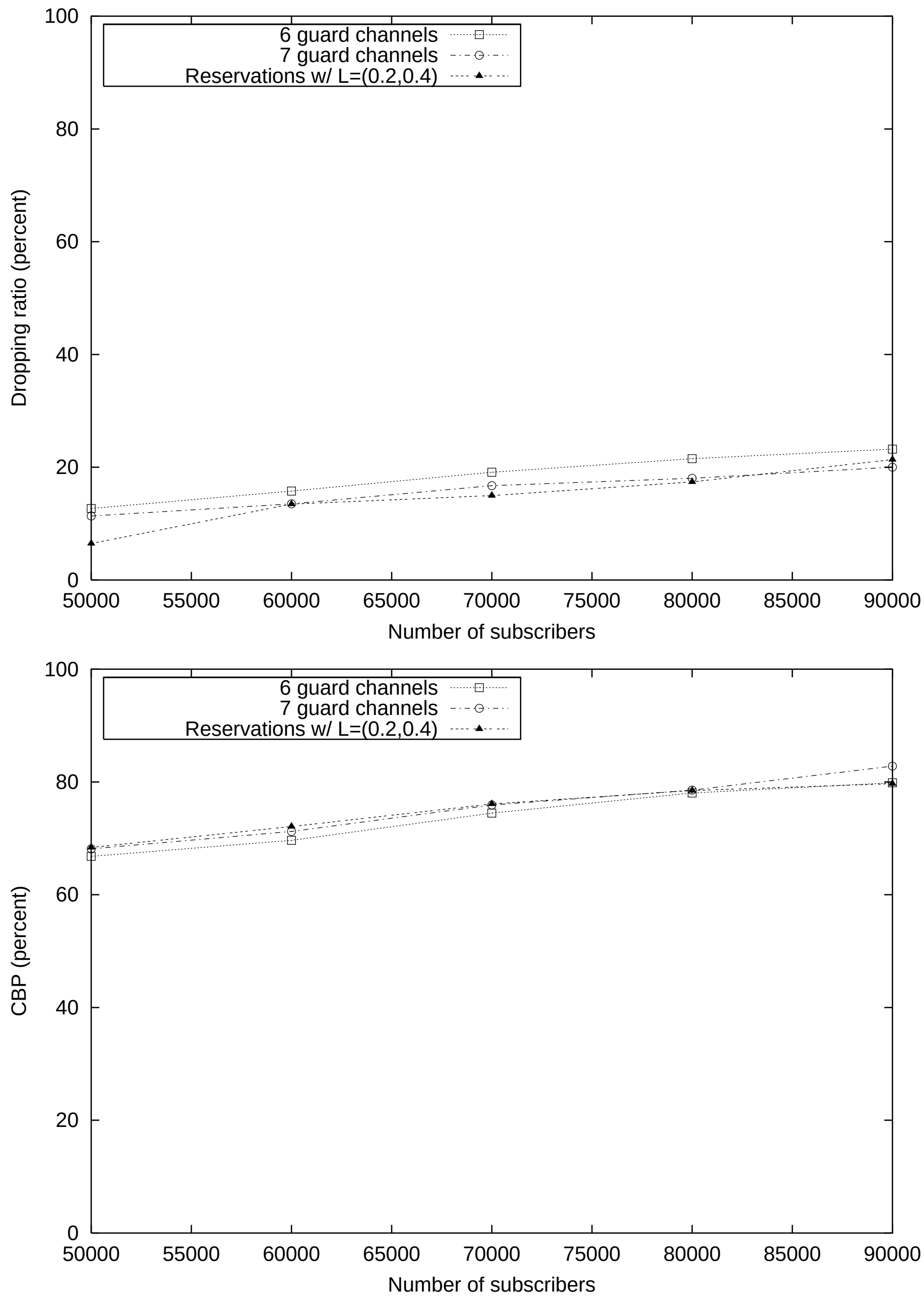


Figure 5.13. Effect of making reservations in terms of maximum dropping and blocking ratios

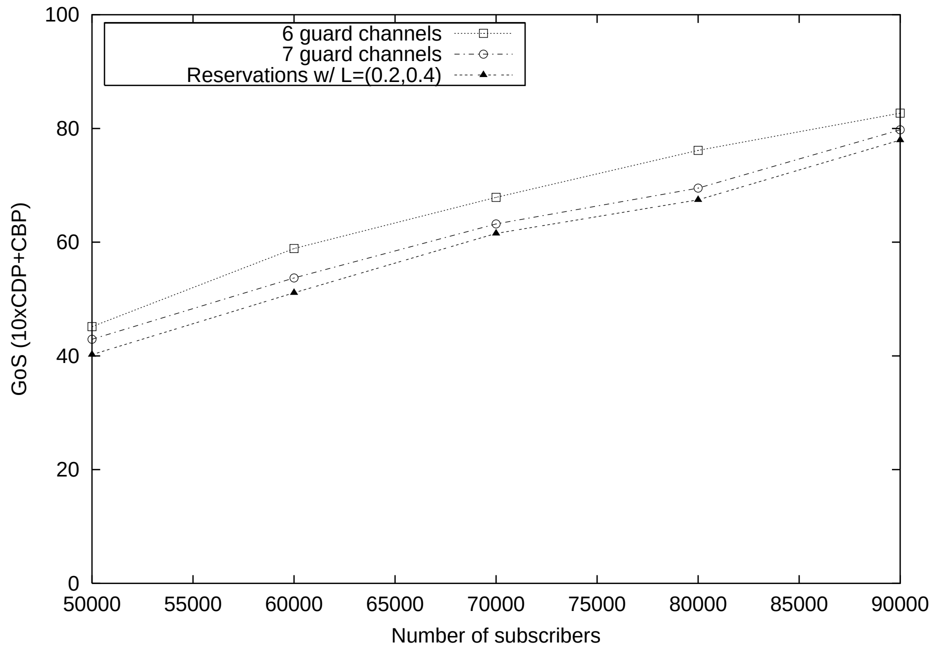


Figure 5.14. Effect of making reservations in terms of GoS

5.3.2.4. Effect of Cell Radius. The effect of cell radius on the system performance was analyzed for both the classical guard channel scheme and the proposed scheme. For the classical scheme, one can observe in Figure 5.17 that both CDP and CBP decrease in direct proportion with cell radius. This is expected since smaller cell radius implies more channels being available over the same service area (See Section 2.1).

The effect of cell radius on the system performance for the proposed scheme was sketched in Figure 5.18. The results are in parallel to the case with the classical scheme, except that the proposed scheme performs better. The results for the classical and proposed schemes are plotted in Figure 5.19 to emphasize the difference. It is apparent from the figure that CDP is directly proportional with cell radius for both schemes. The reason for this relationship is that the wireless resources are less efficiently used for larger cell sizes [15]. One also notice that the proposed scheme performs better than the classical scheme, and the difference between the two schemes is maximum, for the case studied, when cell radius is $0.7\,km$, which corresponds to microcells. As the cell size gets as small as $0.5\,km$, which corresponds to picocells, both schemes approach to zero, and the difference is, therefore, negligible.

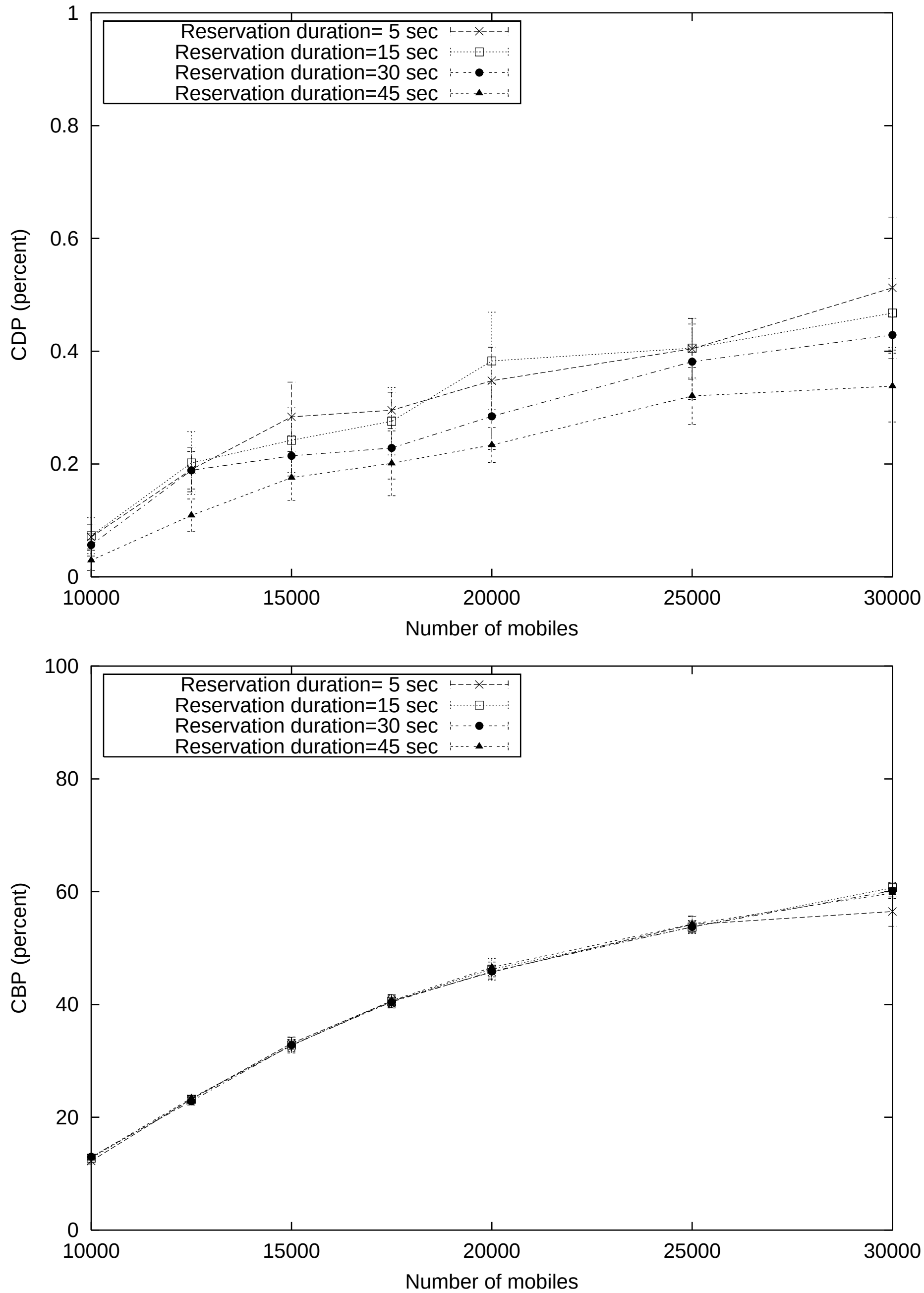


Figure 5.15. Effect of reservation duration

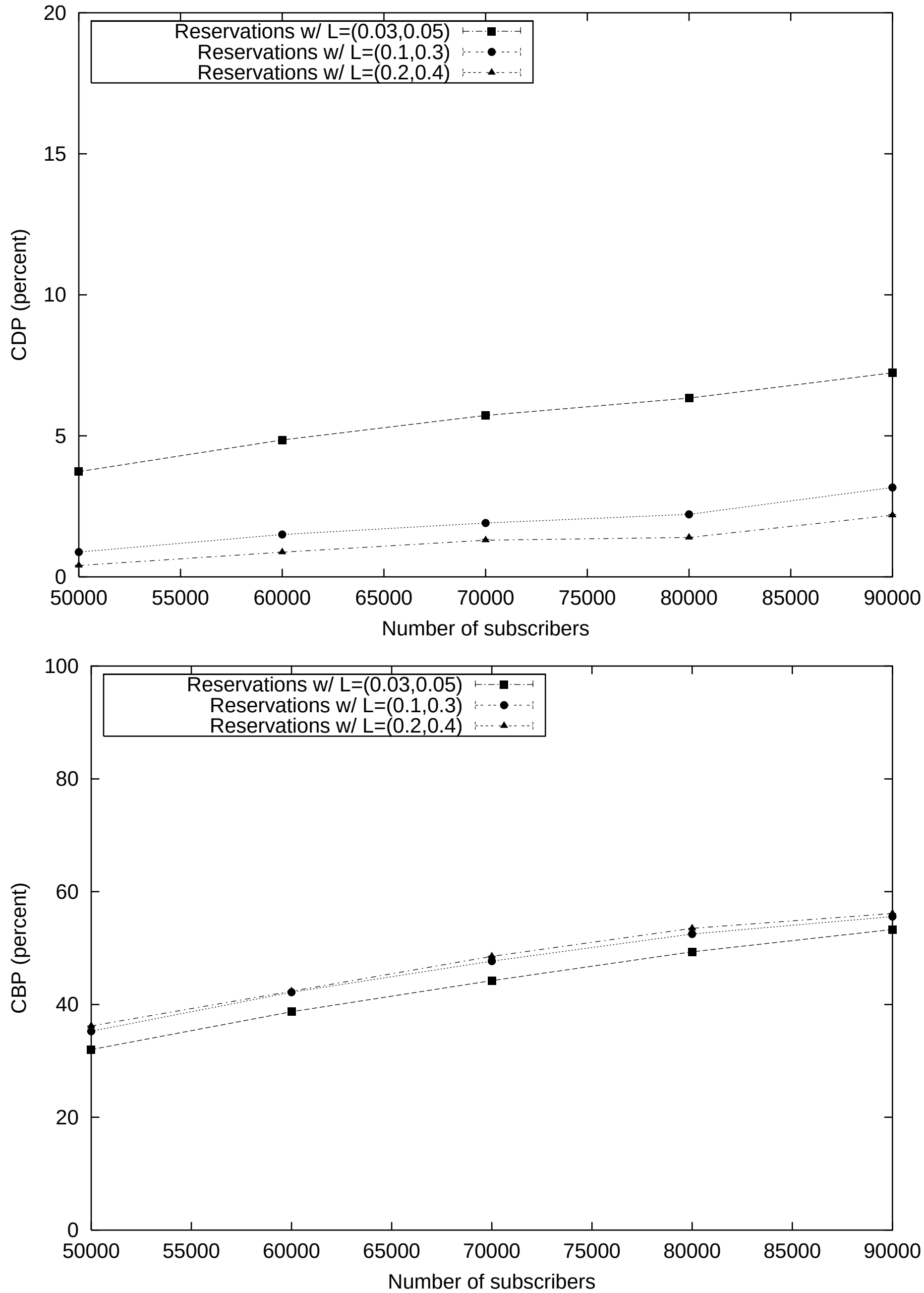


Figure 5.16. Effect of likelihood factors

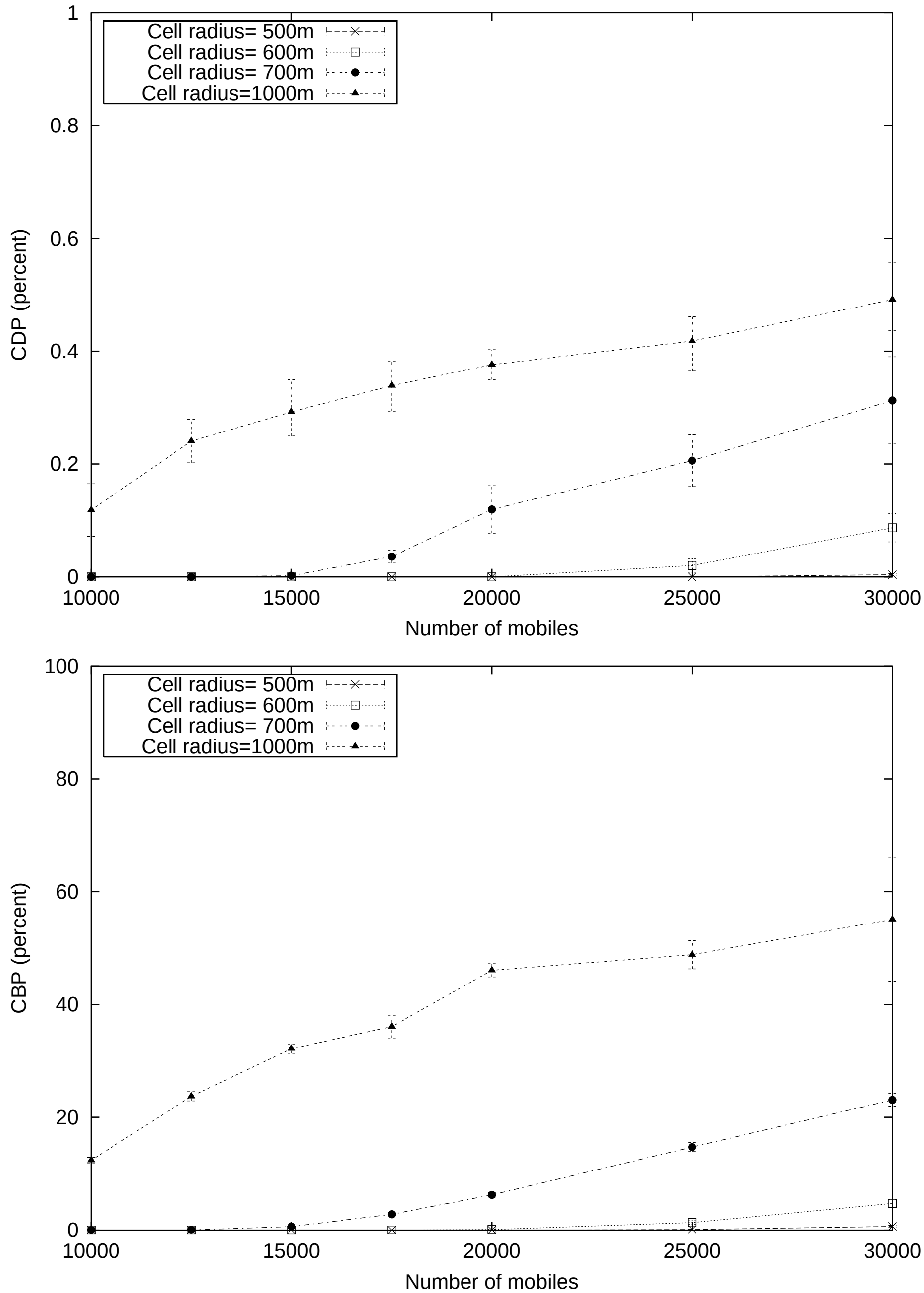


Figure 5.17. Effect of cell radius for the classical scheme

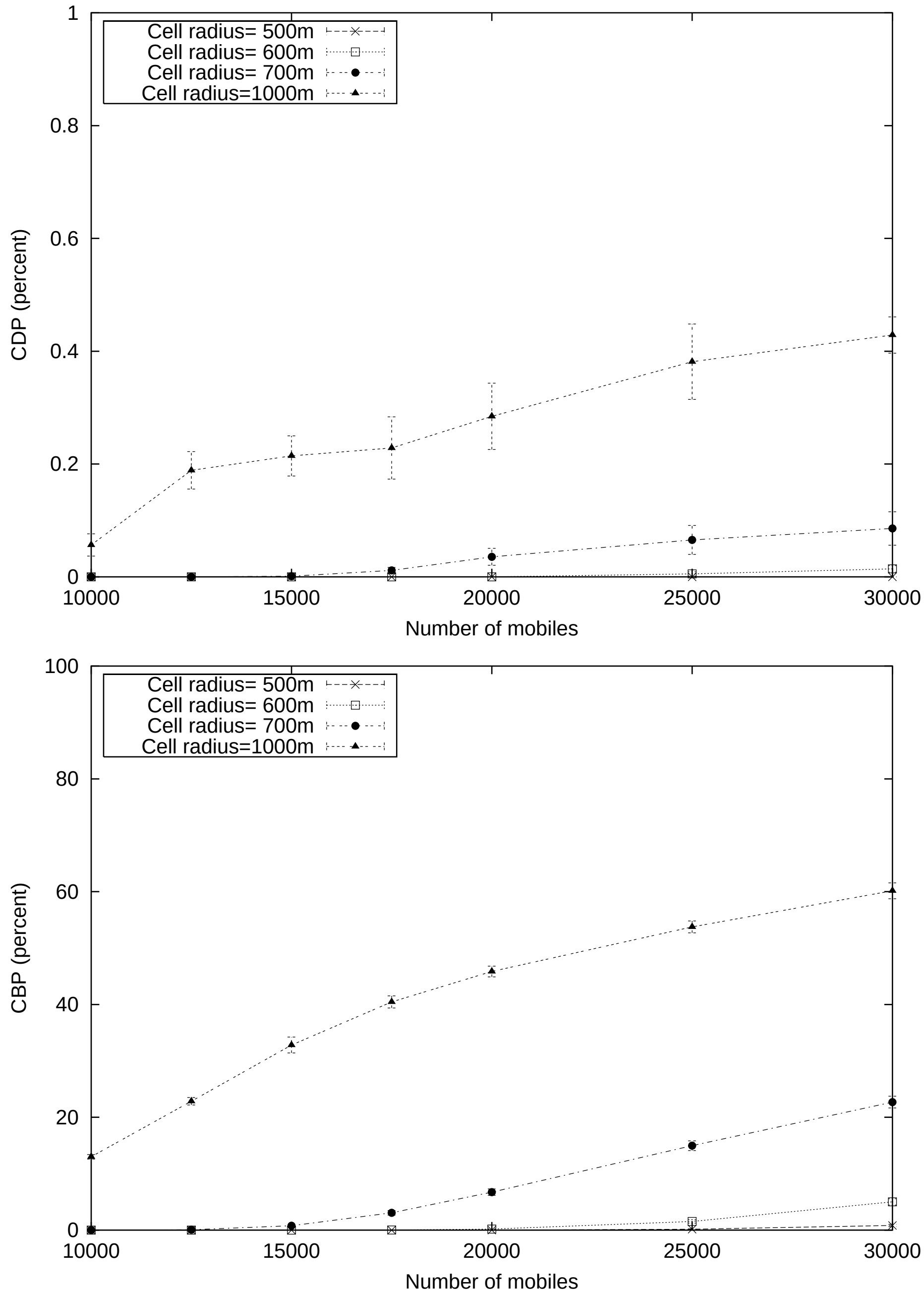


Figure 5.18. Effect of cell radius for the proposed scheme

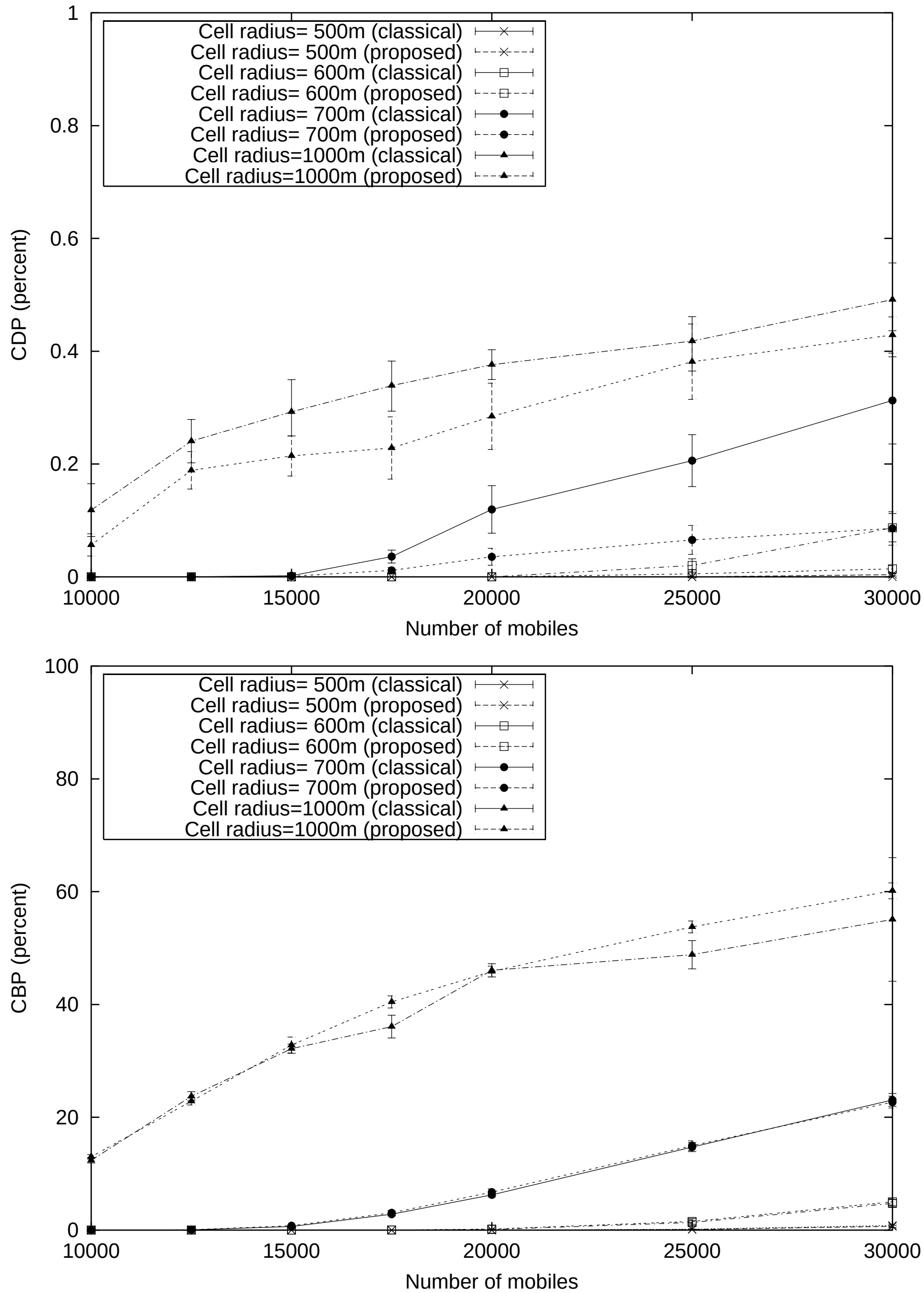


Figure 5.19. Comparison of the effect of cell radius for the classical and proposed schemes

We also analyzed the effect of cell radius when the load, in terms of number of subscribers per cell, is kept constant. The results obtained when the load is fixed to 2500 subscribers/cell are sketched in Figure 5.20. It is apparent that CDP decreases with increasing cell radius as opposed to the direct relationship in Figs 5.6, 5.17-5.19. The direct relationship in the previous cases resulted from the decrease in call traffic per cell as the cells get smaller, representing the effect of decreasing cell radius without altering the subscriber call patterns. The inverse relationship between CDP and cell radius in Figure 5.20 represents the isolated effect of cell radius on CDP by keeping the load per cell constant. One can observe from the figure that the increase in cell radius results in lower CDP since larger cells imply less handoffs. There is a slight increase in CBP as a tradeoff for the decrease in CBP.

5.3.2.5. Effect of Map Type. We also studied the effect of the type of map used for evaluating the system performance as shown in Figure 5.21. The proposed model was studied with the real map and the pure Manhattan-style network, by keeping the number of mobiles, call patterns and the block type change probabilities the same. The service area in the Manhattan-style network is equal to the available service area in the real map, i.e., what remains after empty regions are extracted. It is visible from the graphs that the change in the type of map does not cause a significant change in the trend of the behavior of the system, but both CDP and CBP values differ vastly. The main difference for this difference is that the corners in the Manhattan-style network are very sharp, and a subscriber who re-evaluates his direction just before the corner will not choose to turn at the corner. Even subscribers who re-evaluate their direction just at the corner will choose turning at the corner with a very low probability since turning implies a major change, 90^o, in direction. The results obtained using the Manhattan-style network heavily depend on the simulation parameter “step duration”, since with smaller steps it will be more likely that the subscriber re-evaluates his direction at the corner. On the other hand, when a real map is used, most of the corners are smoother, allowing smaller changes in direction. Furthermore, due to the nature of the Manhattan-style networks, the cells in this type of map cover similar road patterns. As a result of these differences resulting from the two types of map, the experiments using Manhattan-style networks may overestimate or underestimate CDP and CBP with respect to the experiments using the real map (Figure 5.7 and Figure 5.21).

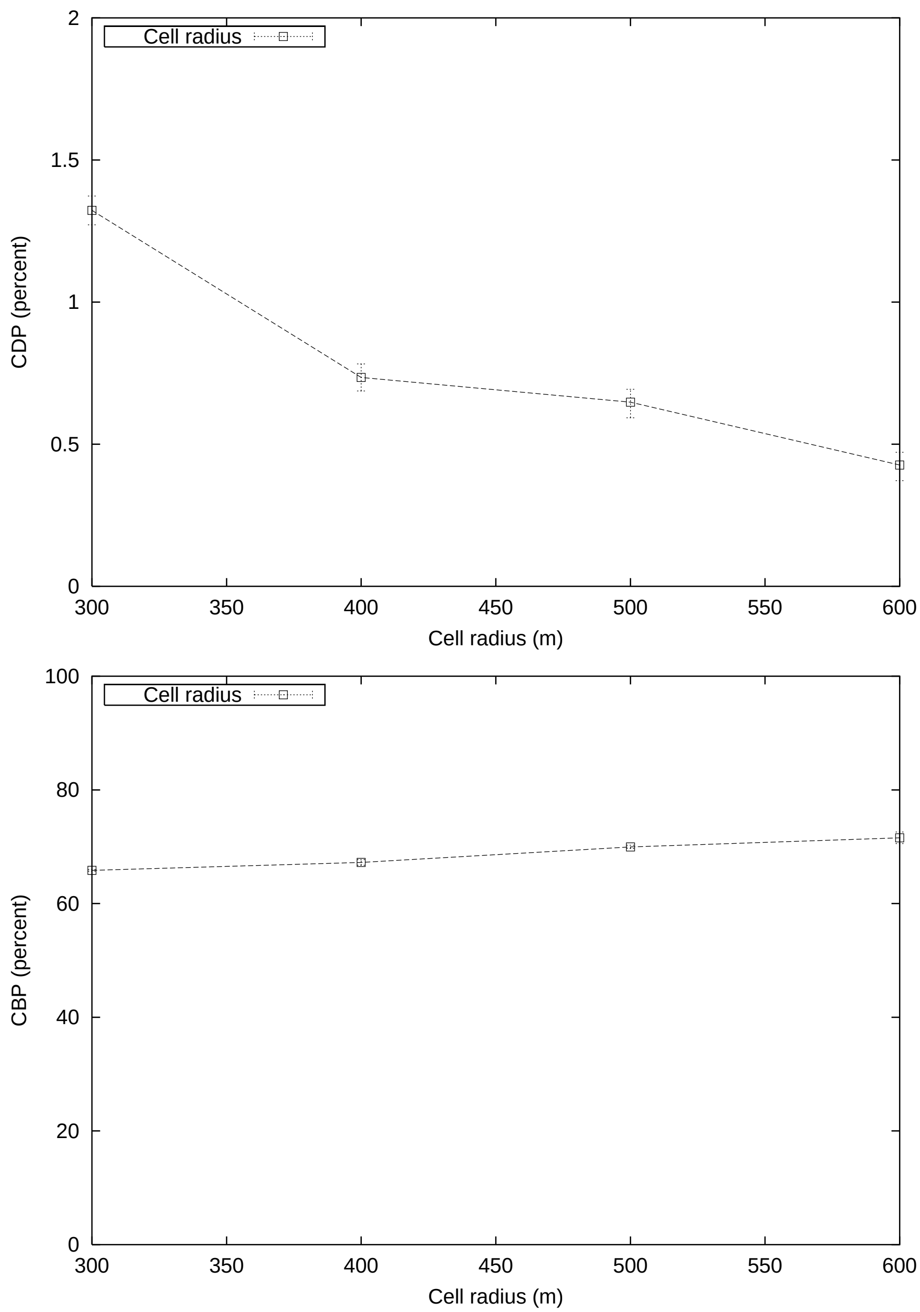


Figure 5.20. Effect of cell radius under constant load

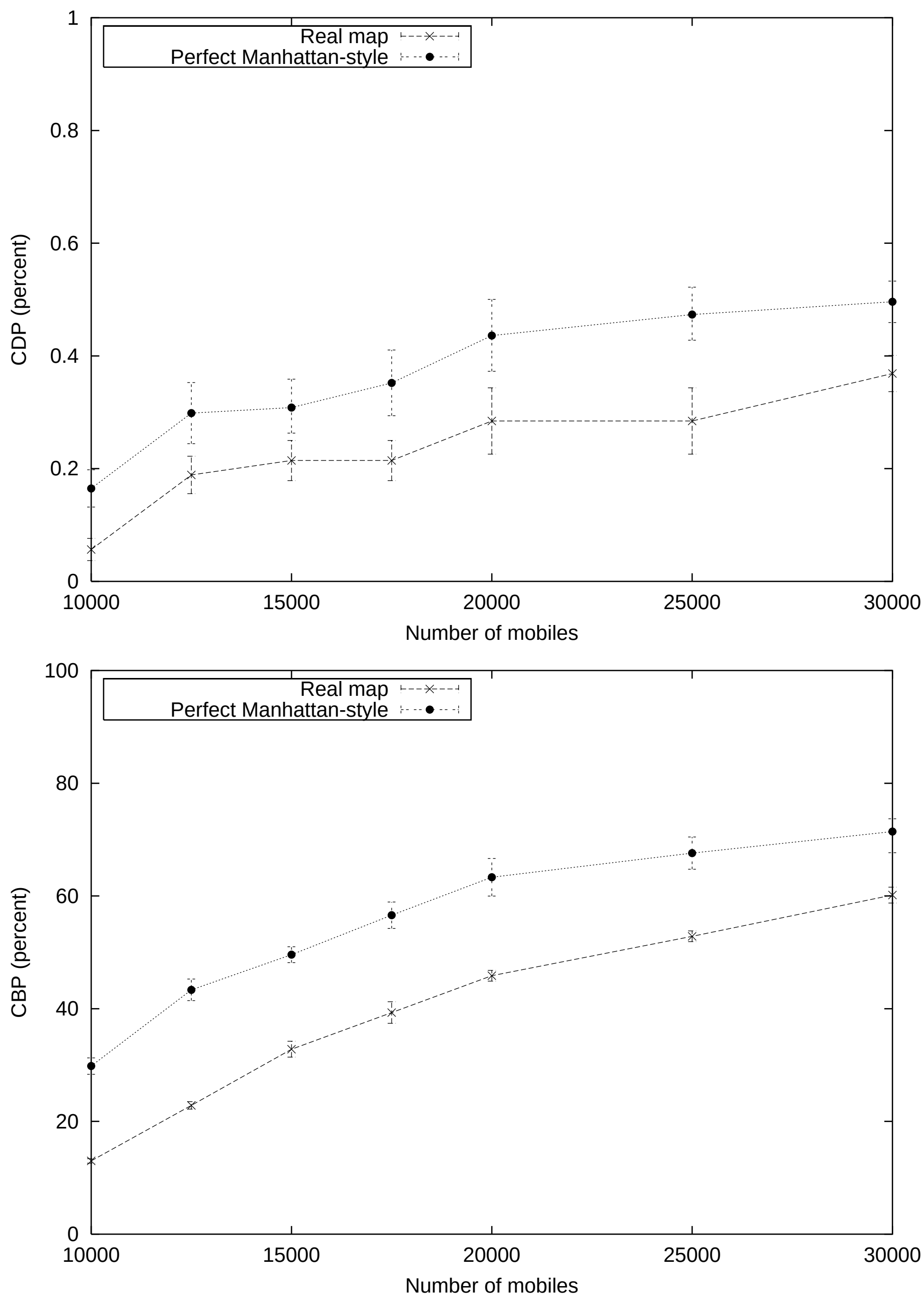


Figure 5.21. Effect of map type

5.3.2.6. Effect of Mobility Pattern. We have analyzed the effect of using our mobility model against the well-known way point mobility model. The mean speed used in the way point model is the mean of the *observed* average speeds of all mobiles in the proposed mobility model. The results are sketched in Figure 5.22. It is apparent that the way point model drastic overestimates CDP and CBP. The more important point to be noted in the graphs is that with the way point model, for all of the three schemes, it is difficult to follow the trend in the system performance as the number of mobile stations increase. Furthermore the variation in the way point model is very large whereas it is almost negligible in the proposed scheme although the number of seeds is the same for both cases. However, our proposed scheme seems to be giving more meaningful results since the proposed call admission scheme has a smoothing effect on the fluctuations due to variations in call traffic. The plain and classical schemes show jumpy behavior with change in load, i.e., the number of subscribers. On the other hand, our proposed mobility model, in addition to giving lower CDP and CBP values, gives steadily increasing CDP and CBP values, for all three schemes, as the load increases.

5.3.3. Sensitivity Analysis

We also made a sensitivity analysis to examine the effect of errors in determining the coordinates of the subscriber to the construction of the reservation area. Remembering that the construction of the reservation area and the determination of the β_1 and β_2 angles in Equation 3.5 are made according to the coordinates of the subscriber, any errors made in the determination of the coordinates, either due to the frequency of sampling GPS data or array antenna system, causes the reservation area to be inaccurate. Thus, channels may be reserved in cells which should not have been considered as candidate, and no channels may be reserved in cells which should have been considered as candidate. We have analyzed the effect of such errors in determining the coordinates on CDP and CBP. Furthermore, we have also analyzed its effect on the ratio of errors in determining the candidate cells to the total number of candidate cells in the reservation area. The results are shown in Figures 5.23-5.24. With an error of approximately 85 m in the coordinates of each subscriber, which may occur if the GPS data is not sampled very often, an error of 18 per cent is made while constructing the reservation area. With an error of 28 m in coordinates, the error rate in construction of the reservation area may be decreased to five per cent, which may be considered reasonable.

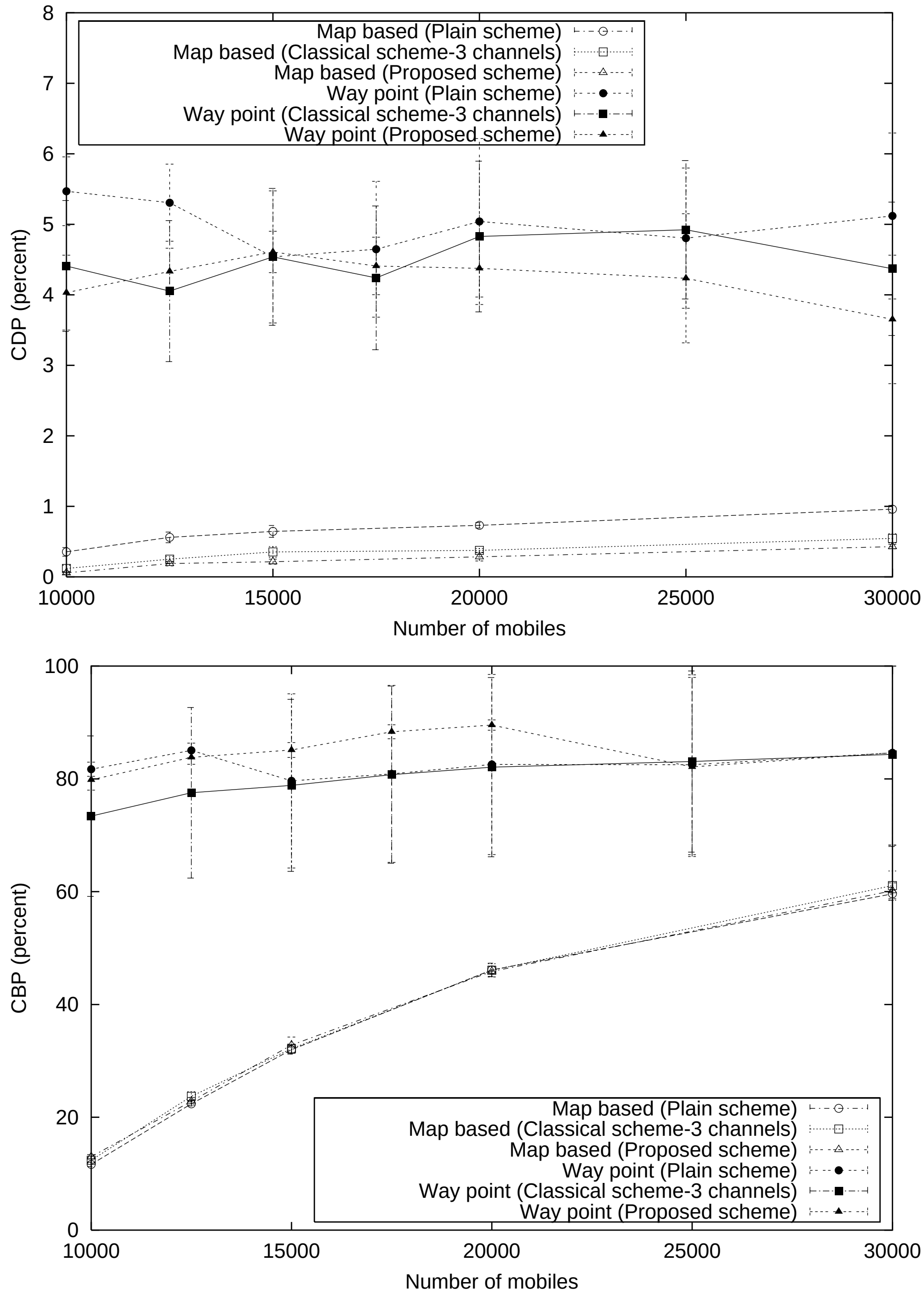


Figure 5.22. Effect of mobility pattern

However, when Figure 5.24 is examined, the reader can note that even an error of 18 per cent in the construction of the reservation area does not cause very significant changes in CDP and CBP. The small change in CDP can be explained by considering the fact that the errors occur only at the cells bordering the reservation area, and the likelihood values for these cells is already very low. The effect on CBP is even lower, because the size of the reservation area does not change with the coordinates of the subscriber.

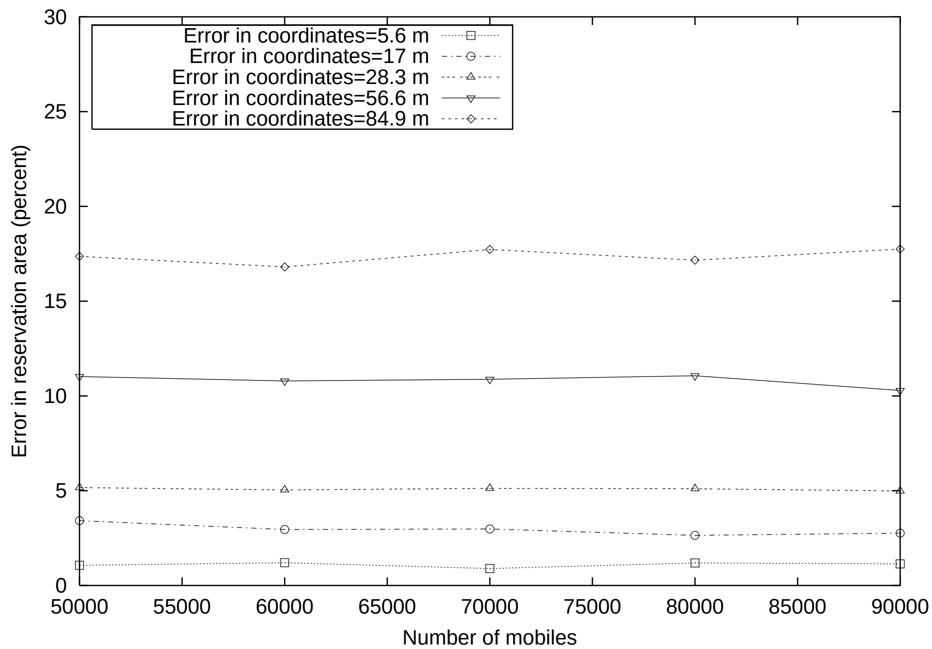


Figure 5.23. Effect of error in coordinates on reservation area

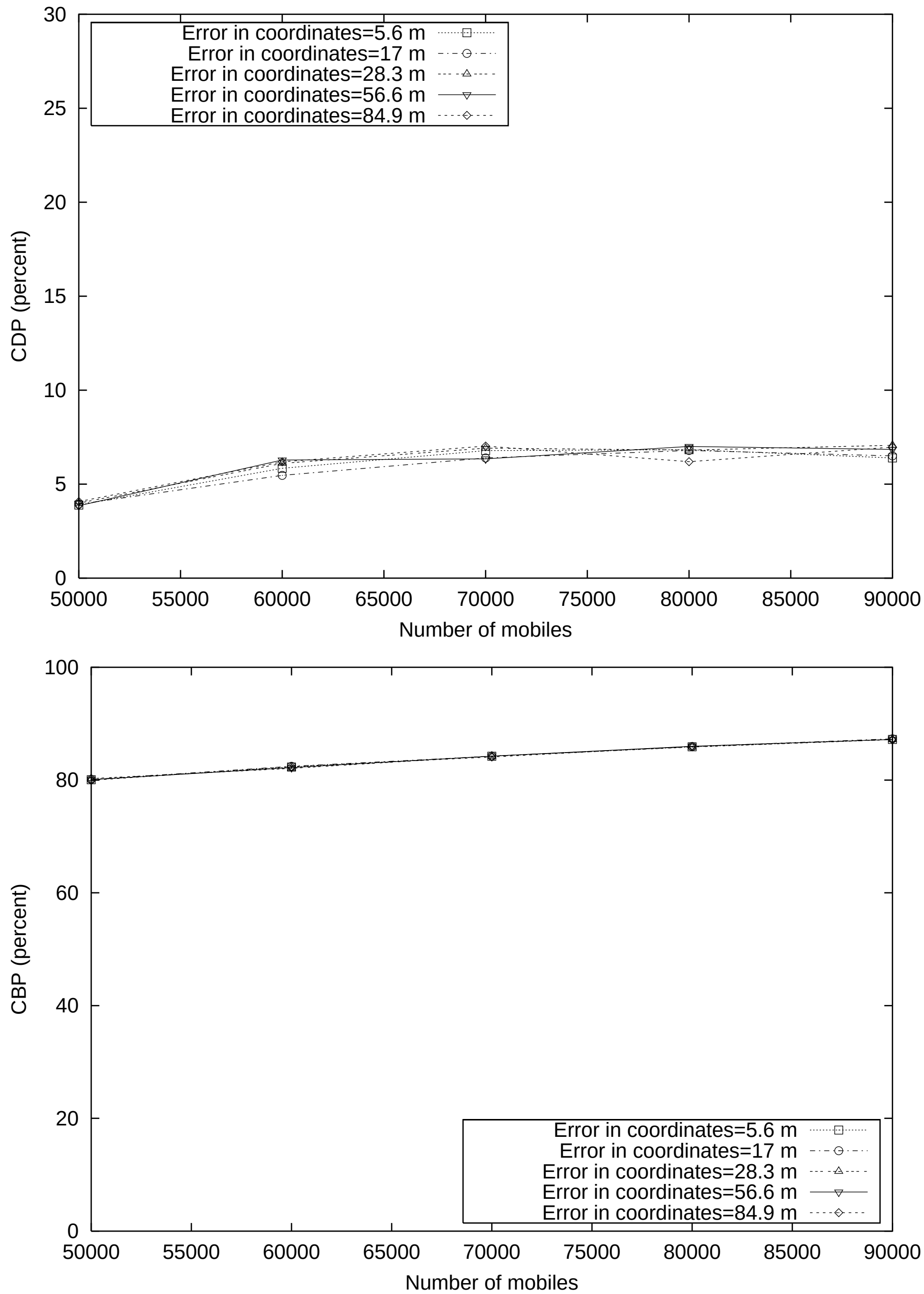


Figure 5.24. Effect of error in coordinates on CDP and CBP

6. CONCLUSIONS

Management of the scarce wireless resources in cellular systems is a major problem. Besides the utilization of these scarce wireless resources, another key factor in the evaluation of the performance of cellular networks is customer satisfaction. The network operator is mainly concerned with channel utilization, customer satisfaction also concerns the network operator indirectly. Since the subscriber is aware of the system load only through blocked and dropped calls, one can define customer satisfaction in terms of the call dropping and call blocking probabilities. Of these two factors, the former is considered to be more annoying than the latter.

The call dropping probability can be decreased by employing guard channels, i.e., some of the nominal channels are made available only to handoff calls. While the handoff call attempts, which would possibly be dropped otherwise, have the chance of grabbing a channel with this approach, it is also highly probable that new call attempts will be blocked although there are free guard channels. In other words, allocating guard channels help decrease the call dropping rate at the expense of higher call blocking rate. Arranging the optimum number of guard channels is a difficult task since the subscriber traffic varies with time and space.

In this thesis, we propose a scheme that adjusts the number of guard channels to be used in each cell via reservations. For each conversing subscriber, a reservation area is constructed depending on the speed, direction and the recent mobility pattern of the subscriber. A reservation request, associated with a likelihood value, is sent to each candidate cell intersected by this reservation area. Thus, the number of guard channels to be allocated in each cell is determined dynamically by aggregating the likelihood values in the received reservation requests. The cost of increasing the blocking rate, by avoiding allocation of unnecessarily many guard channels, results in higher grade of service. We have shown that the proposed scheme performs better than the classical scheme in the sense that lower dropping rate is obtained with respect to the classical scheme with typical number of guard channels, and similar dropping rate is obtained with lower cost, in terms of blocking probability, with respect to the classical scheme with 20 per cent of the nominal channels allocated as guard channels.

The performance evaluation of resource management scheme in cellular networks depends mainly on the mobility model used. Most of the existing mobility models in the literature use unrealistic mobility models like random walk and way point models. The proposed mobility model is realistic in the sense that human behaviors in real life such as moving-in-groups, conscious traveling, inertial behavior and the non-pass-through feature of the physical structures in the terrain are captured. We have analyzed the proposed mobility model against the way point model under the classical and proposed reservation schemes, and shown that our mobility model has a significant effect on the performance criteria.

6.1. Future work

In the reservation based call admission scheme, a reservation area is constructed for each active subscriber. By embedding some of the reservation parameters into QoS bargaining, the cost in terms of increase in call blocking rate can be lowered by making reservations only for the subscribers who demand it, i.e., subscribers who are willing to pay for it. Furthermore, the price of making reservations may be added to the list of factors determining the size of the reservation area so that larger reservation areas, resulting in lower CDP, are constructed for subscribers who are willing to pay more.

The calculation of the likelihood value can be improved by using the ratio of the intersection of the reservation area and the cell area to the total cell area instead of using the distance between the subscriber's current location and the cell center. This change will provide more correct likelihood values for subscribers who are not moving directly towards the cell center, but cross the cell boundary slightly. Another improvement for the likelihood value can be made by employing the *estimated* remaining time of the call in the calculations.

The proposed mobility model can be improved as a future work by using the real cellular layout over the real map. This will help the handoffs to be made in a more realistic model at the expense of a more complicated model. The signal propagation may also be improved at the cost of more complexity.

APPENDIX A: CONSTRUCTING THE RESERVATION AREA

The formulation of the estimated value of change in the direction of the subscriber is given in Equation 3.1. The formulation of the ratio k was also provided in Equation 3.2. Note that, since $\widetilde{\triangle\theta_{t+1}} \in \left[0, \frac{\pi}{2}\right]$, $k \in [0.25,\, 1]$. Thus, owing to the offset $\frac{\pi}{6}$ both in the numerator and the denominator, it is guaranteed that the ellipse never shrinks down to a straight line.

Applying the formulas from basic geometry to Figure 3.2, it directly follows that

$$d = a + c \tag{A.1}$$

$$b = k \cdot a \tag{A.2}$$

$$b^2 = a^2 - c^2 \tag{A.3}$$

$$a > 0,\; b > 0,\; c \geq 0,\; d > 0 \tag{A.4}$$

where,

a is the semi-major axis,

b is the semi-minor axis,

c is the distance between the center of the ellipse and any one of the two foci,

d is the distance subscriber travels with his current speed during the reservation period,

k is the ration in Equation 3.2.

The reader should note that, of the four constraints in Equation A.4, only c is allowed to become zero, which is the case when the ellipse is distorted to a circle.

Substituting Equations A.1 and A.2 in Equation A.3, one gets

$$k^2 a^2 - 2da + d^2 = 0$$

Since $k \in [0.25,\ 1]$, $\sqrt{\triangle}$ exists, and it is

$$\sqrt{\triangle} = \sqrt{4d^2 - 4d^2k^2} \quad \text{(A.5)}$$
$$a_1 = \frac{d}{k^2} \cdot \left(1 - \left|\sqrt{1-k^2}\right|\right) \quad \text{(A.6)}$$
$$a_2 = \frac{d}{k^2} \cdot \left(1 + \left|\sqrt{1-k^2}\right|\right)$$

However, a_2 causes c to become negative, except for $k = 1$ (See Section A.1). Since this contradicts with Equation A.4, and the case $k = 1$ is covered also by a_1, i.e., $\triangle = 0$, there is a unique solution for a, which is a_1 (Equation A.6).

A.1. Proving That a_2 Causes c to Become Negative Except for $k = 1$

Proposition 1 *a_2 causes c to become negative except for $k = 1$.*

Proof. We use the proof by contradiction technique as

$$c = d - a \ > \ 0$$
$$d - \tfrac{d}{k^2} \cdot \left(1 + \left|\sqrt{1-k^2}\right|\right) \ > \ 0$$
$$d \cdot \left[1 - \tfrac{1+\left|1+\sqrt{1-k^2}\right|}{k^2}\right] \ > \ 0$$

Since $d > 0$,

$$1 - \tfrac{1+\left|\sqrt{1-k^2}\right|}{k^2} \ > \ 0$$
$$\left|\sqrt{1-k^2}\right| \ < \ k^2 - 1$$

Since $k \in [0.25,\ 1]$, the RHS is negative except for $k = 1$. However, the absolute value in the LHS is positive for $k \neq 1$. Thus, we get a contradiction and conclude that a_2 causes c to become negative for $k \neq 1$. Similarly, we can prove that a_1 makes c non-negative for

$k \in [0.25, 1]$. For $k = 1$, since the discriminant in Equation A.5 becomes zero, the roots are equal. Therefore, we can use a_1 as the single feasible solution. □

APPENDIX B: FINDING THE CONTROLLING BASE STATION

Since free space signal propagation is being used, the controlling BS for a mobile is found according to the coordinates of the subscriber. In other words, the cell that surrounds MS is its controlling cell. Before discussing the method for finding the controlling BS, we describe our BS indexing convention. Since the origin of the coordinate system is in the lower-left corner, we start enumerating the base stations also from the lower-left corner. Without any special intention, we have used the coordinates $(0, 1)$ for the base station located at the origin. The abscissa value increases increments of one. However, due to the regular hexagonal layout, between the ordinates of two neighboring cells on the ordinate axis, there lies another cell (Figure B.1). In [76], a hypergraph-based method has been proposed for the layout.

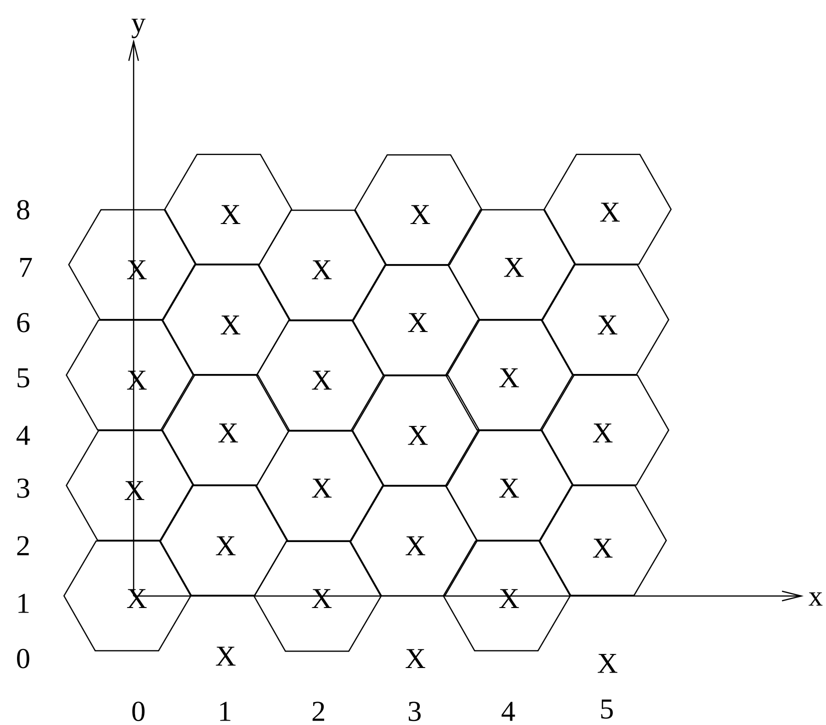


Figure B.1. Indexing the base stations

In order to find the controlling cell in an efficient way, one should draw the parallelogram that surrounds the mobile. This parallelogram is sketched in Figure 4.3 with the corners BS_{LD}, BS_{LU}, BS_{RU} and BS_{RD}. The coordinates of BS_{LD} can be found from the coordinates of the subscriber. For a subscriber with coordinates (p, q), the index (m, n) for its BS_{LD} can be formulated as

$$
\begin{aligned}
m &= p\,div\,\frac{3 \cdot r}{2} \\
n &= \begin{cases} \left(q\,div\,r \cdot \sqrt{3}\right) \cdot 2 + 1 & if\ (x\,mod\,2) = 0 \\ \left(\left(q + \frac{r \cdot \sqrt{3}}{2}\right)\,div\,r \cdot \sqrt{3}\right) \cdot 2 & if\ (x\,mod\,2) = 1 \end{cases}
\end{aligned} \tag{B.1}
$$

It is straight forward to obtain the indices of BS_{LU}, BS_{RU} and BS_{RD} from BS_{LD} as $(m, n+2)$, $(m+1, n+3)$ and $(m+1, n+1)$, respectively. The coordinates of a cell with index (a, b) is formulated as $\left(a \cdot \frac{3 \cdot r}{2}, (b-1) \cdot \frac{\sqrt{3} \cdot r}{2}\right)$. The lines 1, 2, 3, 4 and 5 in Figure 4.3 can be easily formulated, and the controlling BS can be found depending on which side of these lines the subscriber is.

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