A NEW SCHEME FOR PRIORITIZING HANDOFFS IN CELLULAR NETWORKS

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Abstract

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Wireless communication systems are increasingly regarded as essential communication tools that allow users access to the global network at any time without regard to location or mobility. The design of many wireless networks is based on the cellular concept. The implementation of such cellular networks presents new problems that cannot be solved by classical communication theory and that are not found in wired networks. One of these problems is maintaining a connection as mobile terminals move and cross cell boundaries. The process that allows a call in progress to continue as the mobile terminal moves between cells is called a *handoff*. In cellular networks, call admission algorithms play an important role in improving the performance of the network. In this thesis, we present a new call admission algorithm that improves the quality of service in cellular networks by prioritizing handoff call requests over new call requests. This prioritization is based on defining a controlled dropping ratio that attempts to prevent dropping a handoff call until a pre-specified target number of new calls are blocked. The purpose of blocking new calls is to adaptively reserve bandwidth for handoff calls. The aim of this algorithm is to improve the quality of service of cellular networks by minimizing the grade of service, the non-completed call probability, and the channel non-utilization.

The effectiveness of the new call admission algorithm in reducing the handoff dropping probability and the new call blocking probability was studied. Simulation results show the superiority of our algorithm compared to other algorithms proposed in the literature in various scenarios characterized by different traffic loads. The new algorithm is seen to provide lower new call blocking probability, and higher handoff dropping probability compared to the Fixed Threshold Assignment (FTA) and the Adaptive Threshold Assignment (ATA) algorithms that were proposed in [18] and [35], respectively. In this thesis, we used the Grade of Service (GoS) [35], the non-completed call probability P_{ns} [38], and the channel non-utilization as performance

measures. The grade of service is a cost function that increases by a multiplicative factor α the importance of the dropping probability of handoff calls compared to new calls, while P_{ns} is the probability that a call is not completed due to blocking of a new call or dropping of a handoff call. Computational experiments showed that the proposed algorithm had almost the same GoS, a lower value of P_{ns}, and a better channel non-utilization compared to FTA and ATA.

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This thesis is dedicated to my family. I thank my husband Husam for his love, patience, and support during the work of this thesis. I am indebted to my parents for their affection and encouragement. Finally, I am grateful to my lovely daughter Munirah for her love and patience.

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Chapter 1

Introduction

After the introduction of the first mobile telephone service in 1946, the growth of the mobile telephone market has been rapid and the underlying wireless technology is becoming better and increasingly faster [23]. This evolution in wireless communication systems has been driven by a rapidly increasing number of users as well as services that require greatly increased bandwidth. Wireless communications systems are promising to be the primary style of data access technology in the next century. The services to be provided by wireless communication systems include cordless telephones, radio pagers, wireless local area networks, wireless ATM networks, mobile telephones, and satellite communications[40, 23]. The primary function of wireless communication systems is to connect moving terminals to the network using radio signals. The scale of the wireless links of these services vary from a few meters for cordless phones to tens of kilometers for satellite systems. The increased demand for high data-rate services has resulted in an anticipated shortage of already scarce radio spectrum resources. Thus, careful management of these resources is an urgent and critical problem.

The traditional wireless communications system was structured in a fashion similar to television broadcasting where a single powerful transmitter located at the highest spot in an area would broadcast to a radius of up to 50 kilometers. In 1921, the Detroit Police Department was using a crude mobile radio, and mobile communications slowly developed throughout the 1920s, 1930s, and 1940s. The problem had always been that radio frequencies would fill up quickly with voice traffic and interference. Eventually in the early 1970s, the Bell System restructured the wireless communications system in a different way to ease the problem of spectrum congestion. Instead of using one powerful transmitter, the coverage area was divided into smaller coverage areas called *cells*, each using a low-power transmitter. The cellular network derives its capacity from the idea of reusing the same frequency channels in different cells. In this way, cellular networks increase the number of simultaneous calls that can be served at a time while using the same number of frequency channels. However, the reuse of channels is limited by the phenomenon of *co-channel interference*. Thus cells that are too close to each other are not allowed to use the same frequency channel at the same time.

A familiarity with the history of cellular networks is useful in order to appreciate the enormous efforts in developing and improving services offered by cellular networks. In the late 1970s, the first-generation (1G) of cellular networks was deployed in North America (Advanced Mobile Phone System, AMPS), United Kingdom (Total Access Communication System, TACS), West Germany (C-450), and Japan (Nippon Telephone and Telegraph, NTT) [17]. All these cellular networks used analog FM transmission with different deviations and channel spacing for their voice services. As wireless communication became more popular in the late 1980s, the cellular industry was faced with the limitations of the first-generation cellular networks such as capacity bottlenecks and incompatible standards between North America, Europe, and Japan. These limitations were the driving force to develop the second generation (2G) of cellular networks which use digital transmission.

The high capacity in the second generation is obtained from applications of advanced transmission techniques including efficient speech coding and efficient bandwidth modulation techniques [17]. Global System for Mobile Communications (GSM), IS-136 or Digital AMPS (DAMPS), Personal Digital Cellular (PDC), and IS-95 are the second-generation systems. The first three systems are time-division multiple access (TDMA) based systems, while the last system relies on code division multiple access (CDMA) as its air interface. GSM is recognized as the world leader in terms of number of subscribers (183 millions) [34].

First and second generation cellular networks currently provide services for voice communications and low-bit-rate data [36]. The enormous growth of the mobile cellular market over the past 10 years has made first and second generation cellular networks unable to meet future service requirements such as high-speed data services to support multimedia applications. Therefore, the primary focus of the third-generation (3G), *i.e.*, International Mobile Telecommunications in the year 2000 (IMT-2000), is to provide seamless voice, data, and multimedia communications.

Several challenges are facing cellular networks. These include keeping track of the mobile terminals as they move. The cellular network allows users to move and remain connected to the Public Switched Telephone Network(PSTN) via their mobile terminals. This mobility implies adaptability in the cellular network architecture. A mobility management module that locates mobile terminals roaming in the network while simultaneously delivering incoming calls and supporting calls in progress is one of the challenging aspects of cellular networks.

Another challenge is posed by extremely limited spectrum resources. Efficient allocation and management of spectrum resources is a critical factor in achieving high performance and quality of service in cellular networks. Extensive efforts are being employed to develop intelligent channel assignment and frequency reuse algorithms that support the maximal number of subscribers in networks using the limited spectrum resources. One technique that has been used is multiplexing, a technique that allows more than one user to use the same frequency channel within the network as a means of enhancing the cellular network capacity. Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA) are the three basic multiple access techniques in use. The early analog networks used FDMA as the multiple access technology. In the late 1980s, the Cellular Telecommunications Industry Association (CTIA) chose TDMA over Motorola's FDMA as the technology of choice for existing and emerging cellular markets [41]. With the growing technology competition, Qualcomm developed CDMA as an alternative to TDMA [9].

FDMA divides radio bandwidth into a range of frequency channels and is used in the traditional analog cellular system. With FDMA, only one user in any cell is assigned to a particular frequency channel at a time. However, channels may be reused in several cells in the network simultaneously, provided the level of interference caused is acceptable. The second most common technique that uses digital transmission technology is TDMA. It works by dividing a radio frequency into time slots and then allocating slots to multiple calls. In this way, a single frequency can support multiple, simultaneous data channels. In the TDMA and the FDMA multiple access systems, a time slot or a carrier frequency can be considered as a channel. A mix of TDMA and FDMA (TDMA/FDMA) has been adopted as the multiple access scheme for GSM.

The third technique, CDMA, is relatively new and has not yet been widely implemented. It is a digital cellular technology that uses spread-spectrum techniques. Unlike competing systems, CDMA does not assign a specific frequency to each user. Instead, every user uses the full available spectrum. CDMA uses mathematical codes to transmit and distinguish between multiple wireless conversations. Because the conversations taking place are distinguished by digital codes, many users can share the same bandwidth simultaneously. The advanced methods used in CDMA technology improve wireless capacity and voice quality leading to a new generation of cellular networks. However, due to the high cost in implementing CDMA it seems clear that for the near future at least, TDMA/FDMA will remain the dominant technology in the wireless market [9]. In this thesis, we consider cellular networks using TDMA/FDMA as the multiple access technology.

Another challenge is the maintenance of a connection as a mobile terminal moves into a new service area. When the mobile terminal moves towards the cell boundary, its signal strength from its current cell may drop. In such a case, the mobile terminal needs to be transferred to a different cell. The mechanism that transfers an ongoing call from one cell to another is called *handoff*. The handoff procedure should be completed before the signal strength drops below an acceptable level. The deployment of smaller cell size in current cellular networks to accommodate the increase in the number of subscribers caused an increase in the number of cell boundaries crossed which in turn increased the chances of dropping a call due to factors such as the unavailability of free channels.

One of the most important quality of service issues is that service not be cutoff during an ongoing call due to the lack of free channels in the new cell. Therefore, dropping a handoff call is less desirable than blocking a new call. This adds more challenges to cellular networks, and calls for intelligent call admission control algorithms to play a key role in improving the overall system performance. The call admission control algorithms decide whether to accept or reject calls. Some of these algorithms give priority to handoff calls by reserving channels for handoff calls or by queuing handoff calls until a free channel is available. The global objective of call admission control policies is to minimize the handoff dropping probability and to maintain maximum channel non-utilization. Call admission control algorithms that prioritize handoff calls are a cost-effective way of improving the performance of cellular networks. Much effort is being expended to study existing handoff schemes, and to create new ones that meet these challenges.

1.1 Scope of Thesis

In this thesis, we present an efficient call admission algorithm that addresses the problem of reducing the handoff call dropping probability. The proposed algorithm is based on prioritizing handoff calls over new calls by defining a target dropping ratio that will prevent dropping a handoff call until a pre-specified target number of new calls are blocked. The purpose of blocking new calls is to adaptively reserve bandwidth for handoff calls.

As a system performance measure we used the Grade of Service (GoS), which is a cost function that increases by a factor of α the importance of the blocking probability of handoff calls over new calls. Using the GoS as the only performance measure could lead us to prefer reducing the handoff blocking probability at the expense of a great increase in the new call blocking probability, which in turn reduces the total admitted calls and hence the profit derived by the service providers. To bypass this disadvantage, we considered the non-completed call probability (P_{ns}) as a second performance measure to balance between minimizing the dropping probability of handoff calls and minimizing the blocking probability of new calls. We also measured the channel non-utilization of the system which is an important parameter especially from the point of view of the service providers.

Performance analysis of various call admission algorithms is virtually impossible without running simulations. Therefore, several computational experiments were carried out in order to present the characteristics of the proposed algorithm. Simulation experiments were executed to evaluate the performance of the proposed algorithm, to provide evidence that it meets the design goals, and to compare it with other call admission schemes proposed in the literature. Furthermore, the effect of several system parameters on the behavior of the proposed algorithm was studied. Some of the system parameters that were studied are the call arrival rate, the mobile call duration and the mobile average speed.

1.2 Contributions

We first designed a call admission control algorithm, the Maintain-the-Ratio (MR) algorithm that prioritizes handoff call requests over new call requests. The fundamental idea of MR is to force the ratio of the number of dropped handoff calls to the number of blocked new calls to be as close as possible to a pre-specified quantity called *target dropping ratio*. Experiments illustrated that although the MR algorithm reduced the handoff dropping probability, the increase in the new call blocking probability was high. These findings motivated us to devise some modifications to the MR algorithm to avoid the excessive increase in the new call blocking probability. The modified version of the MR algorithm, the Less-than-Ratio (LR) algorithm, preserved the basic idea of MR while giving new calls a higher chance to be served.

Our results can be divided in two parts. In the first part, we offer an in-depth study of the effect of several system parameters on the behaviors of both MR and LR. Experiments showed that MR and LR perform well under high traffic loads.In the second part, we compare the performance of LR with different call admission control algorithms that were proposed in the literature. The performance of the different call admission control algorithms was evaluated in terms of the GoS, P_{ns}, and channel non-utilization under different traffic loads. The LR algorithm is seen to provide lower new call blocking probability, and higher handoff dropping probability compared to the Fixed Threshold Assignment (FTA) and the Adaptive Threshold Assignment (ATA) algorithms that were proposed in [18, 35], respectively. The GoS is a cost function that increases by a multiplicative factor α the importance of the dropping probability of handoff calls compared to new calls, while P_{ns} is the probability that a call is not completed due to blocking of a new call or dropping of a handoff call. Experiments showed that the LR algorithm achieved almost the same GoS, a lower non-completed call probability, and the best channel non-utilization compared to the FTA and ATA algorithms.

1.3 Organization of Thesis

The rest of this thesis is organized as follows: A literature review of cellular networks is presented in Chapter 2. The preliminary concepts of channel assignment schemes and strategies to handle handoffs in cellular systems are also illustrated in Chapter 2. In Chapter 3, the new proposed call admission control algorithms are described along with their proofs of correctness. Further, empirical comparisons with previous call admission algorithms presented in the literature are illustrated in Chapter 3. Chapter 4 presents the results of the computational experiments to study the behaviour of the new algorithm in great detail. The results include the effects of several input parameters on the system performance. Finally, conclusions and directions for future work are presented in Chapter 5.

Chapter 2

Literature Review

There has been a rapid growth of efforts in research and development in wireless systems to enhance the system capacity and to obtain handling capabilities over a large amount of space using wireless media. One solution is for the wireless system coverage area to be partitioned into contiguous regions called cells. Such cellular networks have greatly enhanced the capability of coping with the increasing demand for wireless communication services. This chapter is devoted to cellular networks in general. The fundamentals of cellular communications, channel assignment schemes, and strategies to handle handoffs in cellular systems are presented.

2.1 Fundamentals of Cellular Networks

The key objective while planning a cellular network is to build a network that provides enough frequency bandwidth for the expected number of subscribers, but at the lowest possible cost. A cellular network has available a certain contiguous part of radio spectrum: this available bandwidth is generally divided into a set of frequency channels. In principle, a cellular network can provide services for an unlimited number of subscribers. However, in reality, it can only provide services to a certain fixed number of subscribers. As the number of subscribers increases and approaches the maximum that can be served, some techniques must be developed to accommodate this increase in the number of subscribers. There are various techniques to enhance the capacity of cellular networks. The first technique is *frequency reuse*. In this technique, each cell is allocated a group of frequency channels to be used within the cell, while adjacent cells are assigned channel groups which contain completely different channels. Mobile terminals can simultaneously use the same channel in different cells that are separated from one another by a distance large enough to keep the interference level within acceptable limits. The optimum frequency reuse pattern is governed by the strength of the received signal at a mobile terminal from its base station relative to the signal received from a distant base station using the same channel. The interference resulting from two or more simultaneous transmissions on the same channel is called *co-channel interference* [18].

Another technique is *cell splitting*, a mechanism by which cells are split into smaller cells, each having the same number of channels as the original large cells [17]. Figure 2.1 illustrates the idea of cell splitting.

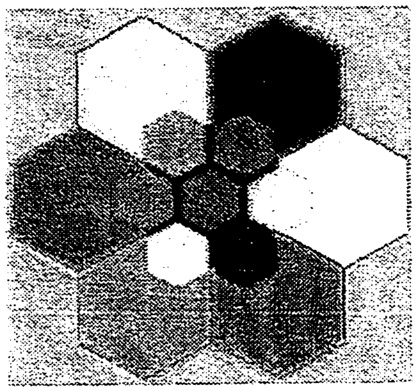

Figure 2.1: Cell splitting

Cell splitting provides an increase in capacity without the need for extra channels, though new issues arise out of smaller cells as the cell radius decreases. First, small cells *(microcells)* encounter a propagation phenomenon called the *corner effect.* The corner effect is distinguished by a sudden large drop in signal strength when the mobile terminal turns around a corner [45]. The corner effect is due to the loss of the *Line Of Sight* (LOS) component. The second issue is the increase in the handoff rate. Handoffs are complicated and costly in terms of delay and utilization of network resources.

Multi-layer networks or hierarchical networks were developed to solve this problem. Large cells *(macrocells)* are implemented to cover a cluster of *microcells*. Macrocells will immediately increase the capacity of the microcell system. Blocked calls in a microcell can retry a connection attempt up to the macrocell. Radio holes that might not be covered by the microcell have a higher probability of connecting to a macrocell. Fast moving mobile terminals can be immediately assigned to the macrocell.

Another alternative technique that handles the increase in the traffic load in wireless systems is to design efficient channel assignment schemes. In these schemes, the total amount of channels available for the cellular network is distributed to cells or calls in different ways. Channel assignment can be static or dynamic. The schemes used differ in performance, flexibility and complexity. However, there is a tradeoff among these qualities, hence each scheme has advantages and disadvantages. Different channel assignment schemes are discussed in detail in Section 2.3.

Cellular networks are composed of several functional entities. The services provided by those entities and a brief explanation of the events that occur when a call is made from or to a mobile terminal are discussed in the next two subsections.

2.1.1 Cellular Network Structure

Cellular networks are usually divided into cells and each cell is served by a *Base Station* (BS). A basic cellular network consists of two parts; wireless part and fixed communication network part. The wireless part is made up of base stations that serve the *Mobile Terminals* (MT) within their coverage range in the cells. The fixed communication network part consists of the *Mobile Switching Center* (MSC), and connections to the *Public Switched Telephone Networks* (PSTN's).

The base station sends and receives information from the mobile terminals and the MSC. Each MSC supervises a group of base stations where it performs a variety of functions involved with call processing. It performs the necessary switching functions required for the MTs located within its supervision area [17]. Furthermore, the MSC maintains the individual subscriber records, the current status of the subscribers, call routing, and billing information. The MSCs together tend to become essentially the brains of the entire network. Each MSC is also involved in the internetworking functions to communicate with the Public Switched Telephone Network (PSTN). The PSTN is the landline network that routes calls between different cellular networks.

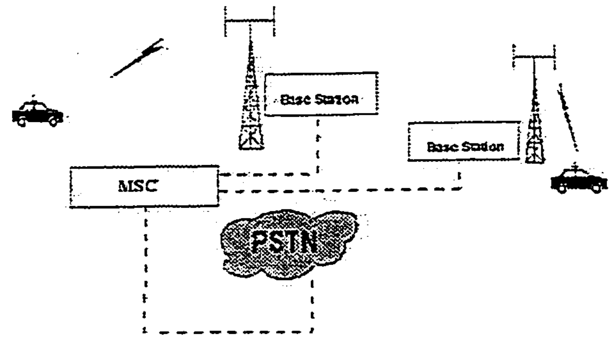

Figure 2.2: Cellular network

2.1.2 Communication Setup and Maintenance

The communication between the BS and MT occurs over frequency channels. Each communication channel uses a channel pair, a *down channel* for transmitting from the BS to the MT, and an *up channel* for transmitting from the MT to the BS. When a call for a MT arrives to the BS, the identity of the MT is broadcast via the down channel. If the target MT recognizes itself, it replies with a positive acknowledgment via the up channel. Then, the BS specifies the channel pair that will be used for the communication. Later, the data transfer and signaling continues on the specified channels. Furthermore, control channels are used for network management messages and some channel maintenance tasks.

The MT initiates a call by sending a message to the BS via the up channel. The BS passes the call request to MSC that handles the rest of the connection request. If the connection with the other party is established, the BS specifies the up and the down communication channels to the initiator MT. The rest is similar to the previous case. The MT releases the channel if the mobile terminal completes the call, or if it moves to another cell before the call is completed. When a MT moves to a new cell while a call is in progresses, the MT is passed to the new base station. This procedure is called *handoff*.

As the MT moves toward the boundary of the cell, the signal strength received from its serving BS is decreased and the MT has to be handed-off to a new BS with a stronger signal. Two thresholds are set for the handoff procedure allowing the MT to keep on requesting an available channel from the new BS before it reaches its failure threshold. The handoff procedure is triggered when the signal level received from the serving BS drops below the first threshold. The handoff must be completed before the signal level drops below the second threshold, which is defined as the minimum signal level required to maintain an acceptable communications quality. If the handoff procedure succeeds, the MT is transferred to the base station from which the received signal level is highest. It is also possible that all channels in the new base station are occupied so the handoff procedure fails. The gap between two threshold values should be chosen very carefully to allow the procedure enough time to be completed. Details and an overview of handoff strategies can be found in Section 2.4.

2.2 Mobility Management

In wireline systems, terminals are static and are located by following the routing information provided at each switch along the path. However, in wireless systems terminals are mobile. Supporting mobility requires some form of tracking to locate mobile terminals within the network. The process of locating the mobile terminals in the entire network and updating the location information is called *mobility management* [3].

Two basic operations are involved in mobility management: *location update* and *terminal paging*. Location update corresponds to the process of reporting the location of mobile terminals as they move [20]. Terminal paging is concerned with the procedures that enable the system to know the current location of a powered-on mobile terminal so that incoming call routing can be completed. Both mobility management operations consume power and bandwidth resources.

Updating the location each time a mobile terminal moves from one cell to another can be very expensive. Therefore, cellular networks divide their coverage area into a number of location areas. Each location area consists of a group of cells. When an incoming call for a mobile terminal arrives, the network first determines the location area for the called mobile terminal and informs it by a paging message. When a mobile terminal moves to a new location area, it must register with the network to indicate its current location. There are three basic location update strategies aimed to minimize the cost of updating locations. The location update strategies could be based on time or on the number of movements or on the distance traveled. Experimental results in [2] demonstrated that the distance-based strategy produces the best result. If the mobile terminal is not registered after the updating period, the mobile terminal is de-registered. When a mobile station is powered off, it performs a detach procedure to inform the network that it is no longer connected.

The cost of location update is proportional to the number of times the user changes its location area while the cost of paging is proportional to the number of calls received. Several schemes aimed to minimize the overall mobility management cost have been proposed in the literature. Those schemes try to achieve a balance between the cost of update and the cost of paging. Akyildiz *et. al* [2] incorporates a movement-based location update policy with a selective paging scheme to decrease the location tracking cost under a small increase in the allowable paging delay. Das and Sen [10] designed an update strategy using a genetic algorithm. This strategy considers the individual user mobility and the call generation patterns to specify a set of reporting areas for each user. The user will update only in his or her reporting area, which minimizes the overall location management cost. More detailed information on mobility management can be found in [1, 3, 20, 23, 39].

2.3 Channel Assignment Schemes

One of the biggest challenges in providing wireless network services is to use the limited number of available frequency channels more efficiently. Cellular technology has enhanced the capability of coping with the increased demands for mobile communications by reusing channels at spatially separated locations. Some resource management tasks performed by cellular systems include channel assignment which is the process of assigning channels either to cells or to calls. A variety of channel assignment strategies have been developed to achieve the objective of increasing capacity and minimizing interference. Channel assignment schemes may be *fixed* or *dynamic* [42, 43].

Fixed Channel Assignment (FCA) is the simplest of all assignment schemes. In this scheme each cell is assigned a fixed number of channels. These are pre-assigned such that two cells within reuse distance of each other do not get the same channel. The whole frequency set is completely used by N cells, and these cells constitute a *cluster*. The number N of cells in a cluster must be determined so that the cluster can be repeated continuously through out the network and the same frequency set is re-used in many different clusters. The typical clusters contain 3, 7, or 19 cells. The number of cells N in each cluster is very important. If the number of cells per cluster is decreased, the number of channels assigned to each cell is increased. However a balance must be found in order to avoid the interference that could occur between neighboring clusters. This interference is produced by the small size of the clusters. The total number of channels per cell depends on the number of available channels and the type of cluster used. Figure 2.3 illustrates a typical cellular layout using FCA strategy with a cluster size of seven and a frequency reuse distance of three. The numbers in the hexagonal cells indicate the channel set used within the cell.

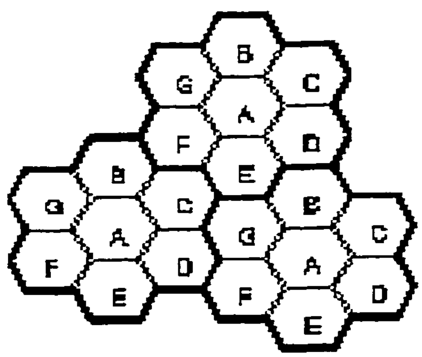

Figure 2.3: Fixed channel assignment

The fixed channel assignment scheme performs well under the assumption of uniform traffic load or high load over the cells [25]. In order to cope with situations where the traffic load is not uniform and where traffic load ratios dynamically change over time, other fixed channel assignments methods which are variation of the basic fixed channel scheme allow channels to be lent to heavily loaded cells.

The channel borrowing schemes can be divided into *simple* and *hybrid* schemes. In the simple scheme, neighboring cells can borrow any free channel for temporary use. Once the call is completed, the channel is returned to the original cell. Under the hybrid scheme, the available channels are divided into two sets, private and borrowable.

The private channels are used only in the local cell, while borrowable channels are allowed to be lent to neighboring cells. A cell can borrow a channel if the following two conditions are true: the lending cell is not already using that channel and any channel within the reuse distance of the borrowing cell is not using the same channel. Some borrowing schemes that have been proposed are discussed next in brief.

Borrow from the Richest (SBR) is a simple borrowing scheme. In this scheme when a cell needs an extra channel it looks for the neighbor with the greatest number of free channels and borrows from it, provided that it can find a non-interfering channel. Another example of a simple borrowing scheme is the *Basic Algorithm with Reassignment (BAR)*. If a free channel becomes available in the cell, a call using a borrowed channel from a neighboring cell is reassigned with the free channel. Two examples of hybrid channel borrowing scheme are the *Borrowing with Directional Channel Locking (BDCL)* and the *Borrowing with Channel Ordering (BCO)*. When a cell borrows a channel in BDCL, it chooses the one which has the least probability to block the same channel in other cells. In BCO, channels in a cell are numerically ordered. When a cell uses its own channels, it starts from the lowest ones. However, when it must give one to a neighbor it gives the highest. BCO is sometimes referred to as *Fixed Preference Allocation algorithm (FPA)*[24]. In this thesis, we are interested in comparing the performance of FPA with our new proposed algorithm. The version of FPA that is simulated in this thesis allows channels to be lent to neighboring cells only for handoff requests. More detailed information on simple and hybrid borrowing schemes can be found in [25, 41, 49].

In contrast to FCA where channels are assigned to cells, channels in *Dynamic Channel Assignment* (DCA) strategy do not belong to any cell permanently. They are kept in a common set and are assigned to the cells according to their needs. The goal of all DCA schemes is to estimate the cost of assigning channels and select a channel with a minimum cost accompanying a tolerable interference level. These DCA schemes differ from one another based on the choice of the cost function. Primarily, the cost function relies on the following: the future blocking probability, the usage frequency of the candidate channel and the reuse distance.

DCA schemes can be classified either as *centralized schemes* or as *distributed schemes*. The first type of scheme has a central controller that uses global information to decide on the channels that have to be assigned to calls. In distributed schemes, base stations use local information from their neighbors and make their channel assignment decisions according to this. Centralized DCA schemes can produce a near optimum channel allocation, however managing DCA in dense small sized cells can overload the central controller. Due to the simplicity of assigning channels by each base station, distributed DCA is more appropriate for small sized cells. Detailed information on DCA schemes can be found in [21, 22, 25].

Comparisons between FCA and DCA have been widely debated in literature. FCA is more powerful in uniform or heavy load traffic, while DCA performs better under low traffic intensity. Channels in FCA are assigned with a maximum reusability of channels which is not the case in DCA. On the other hand, calls in DCA can continue to use the same channel in the next cell if no co-channel interference appears which reduces the handoff calls attempts and thus reduces the forced call termination rates [21]. In this thesis, we restrict ourselves to studying fixed channel assignment strategies.

2.4 Handoffs in Cellular Networks

In cellular networks, the arriving calls fall into two classes: the new arriving call requests and the *handoff calls*. To initiate a call, the mobile terminal must first obtain a free channel from one of the base stations with the strongest received signal. In case the mobile is not granted a channel, the new call is blocked. Since the mobile terminals are free to move, it is not guaranteed that any mobile terminal involved in a communication session will remain in the same cell it once was during the lifetime of the session. When the mobile terminal moves to a new cell, the base station in the new cell has to allocate a channel to the mobile terminal. If no free channels are available at the new base station, the call is dropped. The procedure used for a call in progress to continue as the mobile terminal moves between cells is called *handoff*. In general, the handoff process is caused by the radio link degradation due to the movement of mobile terminals. The average number of handoffs during a session directly depends on the cell radius, mobility pattern of the mobile terminal and the call duration [25, 43, 45].

Handoff procedures can be classified as *hard* or *soft* handoff based on the number of active connections. In hard handoff, a definite decision is made on whether to handoff or not. In the case of a positive decision, the handoff is initiated and executed without allowing the mobile terminal to have simultaneously traffic channel communication with two base stations. Thus there is only one active connection from the mobile terminal at any time. A hard handoff is basically a "break-before-make" process. In soft handoff, a conditional decision is made on whether to handoff or not. The mobile terminal communicates with two or more base stations simultaneously. The handoff is executed when the signal of one base station is considerably stronger than those from others. A simple case of soft handoff while a mobile terminal is moving from cell A to cell B is shown in Figure 2.4.

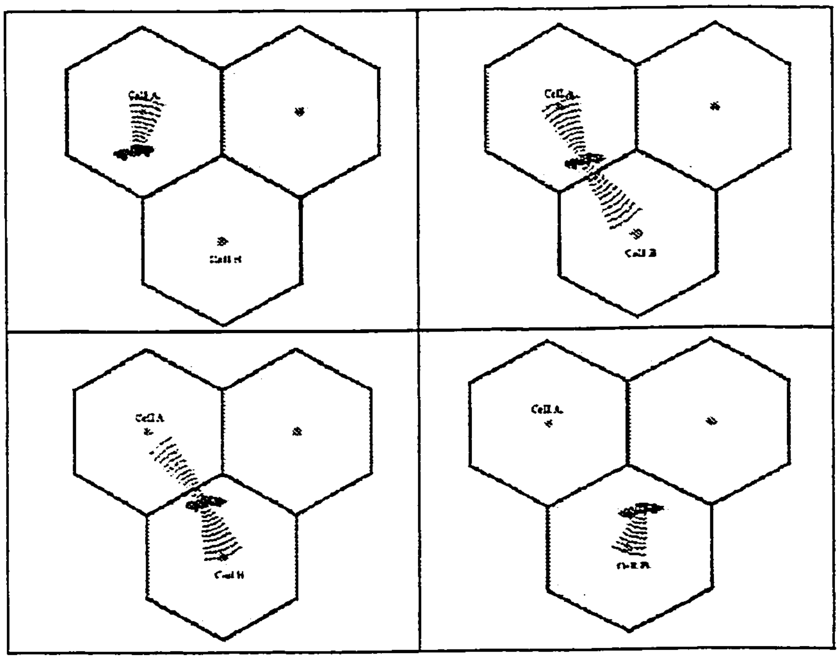

Figure 2.4: The soft handoff procedure

Soft handoffs minimize the risk that the mobile terminal will be lost during the handoff and prevent any short break during this procedure. However on the network side, soft handoffs reduce the overall system capacity since at least two frequency channels are required during this procedure. Soft handoffs also require that mobile terminals have two subsequent decoders to monitor each of the two signals which in turn adds more complexity to mobile terminals [47]. The focus in this thesis is on the hard handoff algorithms since our handoff call requests are based on the mobile terminal distance from the cell boundary rather than on the received signal strength.

The handoff procedure should meet several quality criteria. First, the handoff rate should be kept low, as each handoff causes network overhead to facilitate the handing of a mobile terminal to another base station. This is possible by blocking unnecessary handoff calls which occurs often at the border of a cell, where the received signals of some base stations are almost equal [48]. Another important issue is that the data should not be lost during the handoff. Furthermore, the interruption due to handoff procedure should be minimized in order to make the handoff seamless.

Handoff calls are different from new calls in the sense that there exists an ongoing communication session. One of the most important user concerns is that the service not be cutoff during an ongoing call. Therefore, dropping a handoff arrival is less desirable than blocking a new call. Different ideas and approaches are proposed to reduce the handoff dropping probability. One approach is to design networks that give handoff calls a higher priority over new calls. Cellular networks in which handoff calls are prioritized are called prioritized networks [11]. Another approach is to design networks that have multiple layers of cells to reduce the rate of attempted handoffs [11]. These approaches are discussed in the next two subsections.

2.4.1 Handoff Prioritizing Networks

The effect of handoff on the performance of the system was not taken under consideration in all channel assignment schemes presented in the previous section. Therefore, new channel assignment schemes with handoff prioritization schemes have been proposed to improve the performance of the system. Two simple concepts have been introduced in the literature to reduce the probability of forced termination: the *guard channel concept* and *queuing call concept.*

Guard Channels

The guard channel concept was introduced in the mid-1980s [18] as a simple way to give priority to handoff calls. A fraction of the total available channels in a cell are reserved exclusively for handoff requests. Handoff calls may use all available channels. On the other hand, the new calls get a channel assigned if the number of the channels in use is less than a certain threshold. The value of the threshold directly affects the probabilities of call blocking and dropping. This call admission strategy is referred to as the Fixed Threshold Assignment (FTA) [37, 45]. This strategy has the risk of under-utilizing the frequency channels. Therefore, an efficient estimation method of the optimum number of guard channels is essential. Another drawback of the employment of guard channels, is the increase of the blocking probability of new calls as the number of guard channels increases. This was balanced in [37] by implementing an efficient algorithm which finds the minimum number of channels in each cell that attempts to minimize the dropping probability of handoff calls while keeping the new call blocking under a target ratio.

Oliver and Borras [35] reduce the probability of under-utilizing channels by adaptively changing the number of channels to be reserved in the cell based on information reported by the mobile terminals. This type of information depends on the mobile distance from the cell border, the average mobile speed and the mobility pattern. Another idea of adaptively changing the number of guard channels was presented in [27]. Levine *et. al* [27] used a shadow cluster to estimate future resource requirement and to perform call admission decision. The fundamental idea of the shadow cluster strategy is that each mobile terminal informs its neighboring base stations about its requirements, position and movement parameters. Base stations that are currently influenced are said to form a shadow cluster, the mobile shadow cluster changes dynamically as the mobile terminal moves. Based on the information received from mobile terminals, the base station predicts future handoff calls and only accepts new calls that can be supported.

Epstein and Schwartz [12] compared two types of reservation schemes, the pre-reservation and the post- reservation schemes. Channels are divided into guard channel and a shared channel pool. In the pre-reservation scheme, the handoff call uses the guard channels first. In the case that all guard channels are occupied, handoff calls will compete with new calls for a channel in the shared pool. In post-reservation, both types of calls compete for a channel in the shared pool. If all channels in the shared pool are in use, only handoff calls may use the guard channels. Experimental results demonstrated that the post-reservation scheme is more powerful than the pre-reservation scheme [12].

Queuing of Calls

The queuing of incoming calls due to lack of available channels is another method to increase the overall performance of the system. An important issue in queuing systems is the maximum allowable waiting time in the queue. Queuing handoff calls is possible during the time interval that the mobile terminal spends between the first and second thresholds explained in Section 2.1.2. However, queuing new calls is possible due to the patience of mobile users. Therefore, the maximum allowable waiting time is small for handoff calls and larger for new calls [6, 13]. A careful estimation of the queue length and knowledge of the maximum allowable waiting time in a queue must be taken under consideration when implementing queue systems [45]. Tekinay and Jabbari [44] presented a priority queuing scheme that allows handoff calls to be queued. The signal level the mobile terminal receives from its current base station defines its priority. The power level of queued mobile terminals is monitored continuously and is dynamically changed. The queue is not a FIFO queue, yet mobile terminals waiting for a free channel in the queue are sorted continuously according to their priorities which maintains high performance for handoff calls.

In the literature, a combination of guard channels and queuing schemes has been studied. The performance improvements for guard channel and queuing schemes are compared in [18] for various combinations of parameters and mobility patterns. Some ideas found in the literature that prioritize handoff calls without the employment of guard channels or queuing are discussed next.

Other Handoff Prioritizing Schemes

Lim and Wong [33] presented a handoff algorithm that allows calls moving in opposite direction to swap channels. This algorithm finds a closed path within the immediate neighboring cells that synchronizes reciprocal handoffs and minimizes the need for new channels. The algorithm was extended to find a closed path in cells that are separated two cells away from the current cell, if no closed path was found with the immediate neighbors. The method in [46] describes optimal handoffs decision rule based on the estimation of the trajectory of the mobile terminal and on the signal strength measurements, without waiting for the handoff to occur.

Some admission control strategies as in [7] try to improve the performance of a system by keeping the handoff dropping probability under a pre-specified target. The scheme described in [7] calculates future bandwidth resource requirements to perform call admission decision in cellular networks. This scheme determines the bandwidth to be reserved for handoff calls by estimating the user mobility based on a collective history of handoffs observed in each cell within a specific time window. The time window size is adaptively controlled based on the observed handoff dropping events.

Another way to give priority to the handoff calls is to let the mobile terminal continue to use the same channel in the new cell if all channels are occupied in the new cell [31, 32]. The basic idea of this scheme is to allow channels to be shared between adjacent cells without co-channel interference with other cells. Channels assigned in this scheme have a larger reuse distance to avoid co-channel interference due to channel movement. The system in [31, 32] assumed a linear arrangement of cells. However, extending the idea to two-dimensional cellular network complicates the channel management between adjacent cells.

2.4.2 Hierarchical Cellular Networks

Hierarchical cellular networks employ a special architecture that improves channel utilization without a large increase in infrastructure costs. This type of network provides coverage to the same areas by multiple layers of cells of different sizes. Very dense areas are covered with small cell radii known as *microcells*, whereas *macrocells* provide low bandwidth service over a wide geographical area. An architecture that consist of macrocells (overlay cells) that covers an integer number of microcells (underlay cells) is known as a *hierarchical* or *multi-tier network* [11, 16, 26].

Microcells allow further reuse of frequency channels within a geographical area, resulting in an increase in the network capacity. Therefore, they are used to cover high traffic density areas. High speed terminals may generate a lot of handoffs due to the increase in microcell boundaries crossed. Therefore, macrocells are used to provide a continuous coverage of a service area which reduces the handoff rate of high speed terminals [19]. Two important topics are studied related to this type of network: optimizing the resource management between layers and defining efficient strategies to handle new and handoff calls. One approach of managing resources is to divide channels between the two layers, though this could lead to a loss of trunking efficiency [26]. Another approach is to use a dynamic sharing assignment that allows channels to be shared between different layers but not at the same time [26]. Mobile terminals are instructed to move between microcells and macrocells based on their speeds. Slow mobile terminals are served by microcells while high speed terminals are served by macrocells. If a call cannot be served by the microcell due to the lack of free channels, calls are overflowed to the macrocell [11]. The significant advantage of designing macrocell/microcell overlay system is that it provides a balance between maximizing the number of users per unit area and minimizing the network control load associated with handoff [43, 45].

Some interesting hierarchical networks were combined with the idea of handoff prioritizing networks. Hu and Rappaport [19] described a hierarchical network and gave analytical results for a set of different parameters. The choice of the parameters aimed to present the performance of the system under different conditions. Chang *et. al* [6] analyzed a hierarchical network with finite queues for both handoff and new calls. The guard channel concept was also considered for handoff calls. Ganz *et. al* [16] considered an optimal design of hierarchical networks that minimized the total network cost. An algorithm that evaluates the cost and calculates design parameters such as the optimal cell size and the number of channels assigned to each layer was proposed. A Simulated Annealing technique (SA) was used in [11] to determine the design parameters that minimize the total cost of the hierarchical network.

Hierarchical networks are useful when there are heavy traffic loads with different mobility parameter or different quality requirements. In such cases, it may be cost-effective to build hierarchical networks. With uniform traffic load and average mobility speed, handoff prioritizing networks are more effective [25]. In this thesis, we are interested in designing efficient handoff prioritizing networks.

2.5 Performance Measures

The establishment and management of calls are critical in measuring the quality of service of cellular networks. The current trend in cellular networks is to reduce the cell size to accommodate the increase in the number of subscribers. This generates a higher handoff rate, and makes the achievement of a satisfying level of quality of service more complicated.

The most common performance measure in the evaluation of the quality of service of cellular networks is the *percentage of rejected call requests*. The probability that a new call is not serviced due to unavailability of channels is called *probability of blocking a new call* (P_N) and the probability of a forced termination of a call in progress while moving to a new cell is called the *probability of dropping a handoff call* (P_H). The dropping probability of handoff calls is an important criterion in evaluating the performance of cellular networks. One way to reduce the probability of dropping handoff calls is to design a handoff prioritizing cellular network. In general, these types of networks reduce the handoff failure and increase the blocking of new calls which in turn reduces the total admitted calls. The goal of our research is to design a call admission control algorithm that provides a balance between minimizing the blocking probability of handoff calls and minimizing the dropping probability of new calls.

A performance measure that was widely used in the literature [12, 18, 33, 35] is the Grade of Service (GoS). The grade of service is a cost function that increases by a multiplicative factor α the importance of the dropping probability of handoff calls compared to new calls. It can be defined as in [35]:

$$GoS = P_N + \alpha * P_H.$$

The relative cost α is assigned using the system designer's judgement. Another performance measure that is also used in the literature [18, 38], is the probability P_{ns} that a call is not completed because of either initial blocking at a call attempt or a handoff failure. This probability P_{ns} is defined as in [38]:

$$P_{ns} = P_N + (1 - P_N)P_{drop}$$

where P_{drop} is the probability that a call is dropped due to unsuccessful handoff.

$$P_{drop} = (P_d P_H)/(1 - P_d(1 - P_H))$$

P_d is the probability that a call in the current cell requests a handoff to one of the neighboring cells. The non-completed call probability P_{ns} can be considered as a unified measure of both blocking and dropping effects.

One of the major challenges that is facing network providers is the limited amount of spectrum resources. From the point of view of a network provider, a good way of estimating the efficiency of a channel assignment algorithm is to measure how well the available channels are being utilized. A good algorithm would utilize the most channels most of the time, thus not wasting expensive spectrum resources. Thus, a useful parameter that measures the average number of free channels that are not being used is called *channel non-utilization*, γ, defined as:

γ = average number of free channels in one cell / sec.

Chapter 3

A New Call Admission Control Algorithm

A new call admission control algorithm, the Maintain-the-Ratio (MR) algorithm that prioritizes handoff call requests over new call requests is proposed in this thesis. The MR algorithm uses a controlled dropping ratio that will prevent dropping a handoff call until a pre-specified target number of new calls is blocked. The aim of blocking new calls is to adaptively reserve channels for handoff calls. However, our experiments illustrated that the MR algorithm reduces the probability of dropping handoff calls at the expense of higher blocking probability of new calls. To override this shortcoming, a modified version of the MR algorithm, the Less-than-Ratio (LR) algorithm, that gave new calls a higher chance to be served, was developed. In addition, the LR algorithm has incorporated the idea of guard channels. A noticeable improvement in the blocking probability of new calls is achieved using the LR algorithm. The rest of this chapter is organized as follows: A description of the MR and the LR algorithms along with their pseudocode, and proofs of their correctness are presented in Section 3.1 and 3.2, respectively. Furthermore, the performance of both algorithms is compared with the performance of other algorithms proposed in the literature.

3.1 The MR Algorithm

In this section, we first propose the fundamental idea of the MR algorithm. MR is based on providing a balance between the number of handoff calls dropped and the number of new calls blocked such that the ratio of the number of handoff calls blocked to the number of new calls dropped is within a predefined target range. The MR algorithm requires each base station to keep track of the number of calls that were previously dropped in order to calculate the number of handoff calls to be dropped (H_d) and the number of new calls to be blocked (N_b) in the next step. The decision process for the acceptance of handoff and new call requests depends on the total number of handoff and new calls that were previously dropped (D_H) or blocked (D_N), the number of handoff call requests (H), new call requests (N) and the number of free channels (F). The MR algorithm attempts to block (X) new calls before dropping one handoff call. The aim of the MR algorithm is to keep the number of new calls dropped (D_N) between XD_H and $X(D_H+1)$. We say that the dropping ratio *falls in the target range* whenever D_H and D_N meet the condition given by (1).

$$XD_H \leq D_N \leq X(D_H+1)$$

$$\frac{D_H}{D_N} \leq \frac{1}{X} \leq \frac{(D_H+1)}{D_N} \tag{1}$$

MR is divided into two cases. The first case, where the current dropping ratio falls in the target range is the simple case. The second case, where the current dropping ratio does not fall in the target range is a more complicated case. In the first case, the algorithm calls the *MaintainTheRatio* procedure to find the number of calls to be dropped in order to maintain the dropping ratio. In the second case, where the dropping ratio does not fall in the target range, the algorithm calls the *GetInToTargetRange* procedure that attempts to get the dropping ratio to fall in the target range as much as possible by calculating the tentative number of new and handoff calls to be dropped. If the number of remaining calls that are to be accepted is more than the number of free channels, then the *MaintainTheRatio* procedure is called to find the number of calls to be dropped. The pesudocode of the MR algorithm is shown in Figure 3.1.

The MR algorithm aims to maintain the dropping ratio within a pre-specified target range. In normal cases, where the number of handoff call attempts is close to the number of new call requests, the algorithm is able to maintain the dropping ratio to be within the pre-specified target range. However, in extreme cases, where the base station predominantly receives either handoff call requests or new call requests, the MR algorithm would not be capable of maintaining the dropping ratio within the target range. For example, if the dropping ratio $\frac{D_H+1}{D_N}$ is equal to $\frac{1}{X}$ and the base station receives only new calls, then only new calls can be blocked (or accepted), while no handoff calls can be dropped, as there were no handoff attempts. Thus, D_H would stay the same while D_N would increase, causing the dropping ratio to fall out of range. However, our experiments illustrated that under uniformly distributed traffic loads, the MR algorithm was capable of maintaining the dropping ratio within the desired target range (see Chapter 4). At the same time, we prove that our algorithm succeeds in keeping the dropping ratio in the target range whenever possible and in keeping it as close to the target range as possible otherwise.

We proceed to describe the algorithm in detail. In order to avoid dividing D_H by zero, each base station actually starts using the MR algorithm when the number of new calls blocked, D_N is greater than zero. If the number of new calls blocked is zero, then the base station will follow the behavior of the fixed threshold algorithm with one guard channel. The pseudocode of the *MaintainTheRatio* procedure along with the proof of its correctness is presented in the next subsection.

3.1.1 MaintainTheRatio Procedure

If the dropping ratio falls in the target range and the total number of calls requesting services is greater than the number of free channels available in the base station, then the MR algorithm will call the *MaintainTheRatio* procedure. The pseudocode of the *MaintainTheRatio* procedure is presented in Figure 3.2.

The *MaintainTheRatio* procedure aims to keep the dropping ratio within the target range. We present the key idea here. Note that at most F calls can be accepted, since F is the number of available channels. The remaining calls must all be dropped, and we calculate M_{Hd} to be the number of handoff calls to be dropped so that they are at most $\frac{1}{X}$ of the total number of calls to be dropped. Similarly, N_b is the num-

```
The MR Algorithm (int H, int N, int F, int D_H, int D_N)
                {
                if D_H/D_N ≤ 1/X ≤ (D_H+1)/D_N
                  {// In this case, the dropping ratio falls in the target range
                  If (N + H) ≤ F
                    { Accept all calls
                    }
                  else
                    { MaintainTheRatio(H, N, F, D_H, D_N)
                    }
                  }
                else
                  { // In this case, either D_H/D_N > 1/X, or (D_H+1)/D_N < 1/X
                  GetInToTargetRange(H, N, F, D_H, D_N)
                  }
                }// end of the MR Algorithm
```

Figure 3.1: The pseudocode of the *MR* algorithm

ber of new calls to be blocked. If the actual number of handoff call attempts is less than M_{Hd} we simply drop all handoff calls, and accept as many new calls as possible, *i.e.*, F new calls. Similarly if the actual number of new call arrivals is less than N_b we simply block all new calls, and accept as many handoff calls as possible, *i.e.*, F handoff calls. The only remaining situation is where we *can* drop handoff calls and new calls as calculated. In this case, it may be necessary to make a small adjustment in order to keep the dropping ratio in the target range.

Definition 3.1. Let N, H, F, and X be the number of new calls, number of handoff calls, number of free channels, and number of new calls to be dropped before dropping a handoff call, respectively. We define the maximum number of handoff calls to be dropped (M_{Hd}) as:

$$M_{Hd} = \lfloor \frac{N + H - F}{X + 1} \rfloor \tag{2}$$

The number of handoff calls to be dropped (H_d) is at most M_{Hd}, and the number of new calls to be blocked (N_b) is $(N + H - F - M_{Hd})$ which is at least $M_{Hd}X$ as shown in Lemma 3.1. Let the total new number of handoff calls to be dropped be D'_H and the total number of new calls to be blocked be D'_N. Theorem 3.1 shows

// pre-condition $\frac{D_H}{D_N} \leq \frac{1}{X} \leq \frac{(D_H+1)}{D_N}$ and $(N + H) > F$

MaintainTheRatio (int H, int N, int F, int D_H, int D_N)

{ $M_{Hd} = \lfloor (N + H - F)/X \rfloor$

$H_d = M_{Hd}$

$N_b = N + H - F - M_{Hd}$

1. if $(H \geq M_{Hd})$ *and* $(N \geq N_b)$

{

$D'_H = D_H + H_d$

$D'_N = D_N + N_b$

1.1. if $(\frac{D'_H+1}{D'_N} < \frac{1}{X})$

{// In this case, some adjustment is made to keep $\frac{D'_H+1}{D'_N}$ as large as possible

$r = \lceil \frac{D'_N - X(D'_H+1)}{X} \rceil$

1.1.1. if $(H \geq (M_{Hd} + r))$

{

$H_d = M_{Hd} + r$

$D'_H = D_H + M_{Hd} + r$

}

1.1.2. else

{// In this case, $(H < (M_{Hd} + r))$

$D'_H = D_H + H$

$D'_N = D_N + max(max(0, N - F), X(D_H + H) - D_N)$

}

}

}

2. else if $(H < M_{Hd})$

{// In this case, all handoff calls are dropped

$D'_H = D_H + H$

$D'_N = D_N + N - F$

}

3. else

{//In this case, $(N < N_b)$. Therefore, all new calls are blocked

$D'_H = D_H + H - F$

$D'_N = D_N + N$

}

}// end of MaintainTheRatio

Figure 3.2: The pseudocode of the *MaintainTheRatio* procedure

that *MaintainTheRatio* procedure retains the dropping ratio inside the target range as much as possible.

Theorem 3.1. *Let $\frac{D_H}{D_N} \leq \frac{1}{X} \leq \frac{D_H+1}{D_N}$ and $(N+H) > F$. Then the MaintainTheRatio procedure gets the new dropping ratio $\frac{D'_H}{D'_N}$ and $\frac{D'_H+1}{D'_N}$ into the target range as much as possible.*

Proof. Let $M_{Hd} = \lfloor \frac{N+H-F}{X+1} \rfloor$ and $N_b = N + H - F - M_{Hd}$. If $\frac{D_H}{D_N} \leq \frac{1}{X} \leq \frac{D_H+1}{D_N}$ and $(N+H) > F$, then three cases can occur:

1. $H \geq M_{Hd}$ and $N \geq N_b$. In this case, Lemma 3.3 proves that $\frac{D'_H}{D'_N} \leq \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.

2. $H < M_{Hd}$. In this case, Lemma 3.4 proves that $\frac{D'_H}{D'_N} \leq \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.

3. $N < N_b$. In this case, Lemma 3.5 proves that $\frac{D'_H+1}{D'_N} \geq \frac{1}{X}$ and $\frac{D'_H}{D'_N}$ is as small as possible.

$\square$

Lemmas 3.1 and 3.2 are used in the proofs of Lemmas 3.3- 3.5 which establish the above theorem.

Lemma 3.1. *Let $N_b = N + H - F - M_{Hd}$. Then $N_b \geq M_{Hd}X$.*

Proof. Suppose instead that $N_b < M_{Hd}X$. This means that $N + H - F - M_{Hd} < M_{Hd}X$. That is , $M_{Hd} > \frac{N+H-F}{X+1}$ which contradicts (2). $\square$

The following general lemma is used extensively in several of our proofs.

Lemma 3.2. *Let a, b, c, d, y , and z be positive integers.*
(a) If $\frac{a}{b} \leq \frac{c}{d}$ and $\frac{y}{z} \leq \frac{c}{d}$, then $\frac{a+y}{b+z} \leq \frac{c}{d}$.
(b) If $\frac{a}{b} \geq \frac{c}{d}$ and $\frac{y}{z} \geq \frac{c}{d}$, then $\frac{a+y}{b+z} \geq \frac{c}{d}$.

Proof. (a) We claim that $\frac{a+y}{b+z} - \frac{c}{d} = \frac{ad+yd-cb-cz}{d(b+z)} \leq 0$. Since the denominator is positive, we will just study the numerator. The numerator $[ad+yd-cb-cz]$ is negative since $ad \leq cb$ and $yd \leq cz$.

(b) In this case, we claim that $\frac{a+y}{b+z} - \frac{c}{d} = \frac{[ad+yd-cb-cz]}{[d(b+z)]} \geq 0$. Since the denominator is positive, we will just study the numerator. The numerator $[ad+yd-cb-cz]$ is positive since $ad \geq cb$ and $yd \geq cz$. $\square$

The following lemma shows that if $\frac{D_H}{D_N}$ is in the target range and H is at least M_{Hd} and N is at least N_b, then $\frac{D'_H}{D'_N} \leq \frac{1}{X}$. However, $\frac{D'_H+1}{D'_N}$ might be less than $\frac{1}{X}$. If so, the procedure tries to correct the dropping ratio, so that $\frac{D'_H+1}{D'_N}$ falls in the target range. If that is impossible, the procedure makes $\frac{D'_H+1}{D'_N}$ as large as possible.

Lemma 3.3. *Let $H \geq M_{Hd}$, $N \geq N_b$, and $\frac{D_H}{D_N} \leq \frac{1}{X} \leq \frac{D_H+1}{D_N}$. Then $\frac{D'_H}{D'_N} \leq \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.*

Proof. In this case, $N \geq N_b$. Thus, $N \geq M_{Hd}X$ and $\frac{H_d}{N_b} \leq \frac{M_{Hd}}{M_{Hd}X} = \frac{1}{X}$. By Lemma 3.2, since the dropping ratio $\frac{D_H}{D_N} < \frac{1}{X}$ and $\frac{H_d}{N_b} \leq \frac{1}{X}$, the new dropping ratio $\frac{D'_H}{D'_N} = \frac{D_H+M_{Hd}}{D_N+N_b} \leq \frac{1}{X}$. However, if $\frac{D'_H+1}{D'_N} < \frac{1}{X}$, then the procedure attempts to correct the dropping ratio by dropping a suitable number of handoff calls such that $\frac{D'_H+1}{D'_N}$ is as large as possible.

If $\frac{D'_H+1}{D'_N} < \frac{1}{X}$, then two cases could occur, either $H \geq (M_{Hd}+r)$ or $H < (M_{Hd}+r)$ where $r = \lceil \frac{D'_N - X(D'_H+1)}{X} \rceil = \lceil \frac{D_N+N_b-X(D_H+M_{Hd}+1)}{X} \rceil$. If the procedure is able to drop r extra handoff calls, then the dropping ratio falls in the target range. However, if it is impossible to drop r additional handoff calls, then by dropping all the handoff calls $\frac{D'_H+1}{D'_N}$ is as large as possible. In the first case:

$$\begin{aligned}
\frac{D'_H}{D'_N} &= \frac{D_H+M_{Hd}+r}{D_N+N_b} \\
&\leq \frac{D_H+M_{Hd}+(\frac{D_N+N_b-X(D_H+M_{Hd}+1)}{X})+1}{D_N+N_b} = \frac{X(D_H+M_{Hd})+D_N+N_b-X(D_H+M_{Hd})-X+X}{X(D_N+N_b)} = \frac{1}{X}.
\end{aligned}$$

$$\begin{aligned}
\frac{D'_H+1}{D'_N} &= \frac{D_H+M_{Hd}+r+1}{D_N+N_b} \\
&\geq \frac{D_H+M_{Hd}+(\frac{D_N+N_b-X(D_H+M_{Hd}+1)}{X})+1}{D_N+N_b} = \frac{X(D_H+M_{Hd})+D_N+N_b-X(D_H+M_{Hd})-X+X}{X(D_N+N_b)} = \frac{1}{X}.
\end{aligned}$$

This proves that in the first case the new dropping ratio falls in the target range. In the second case, $H < (M_{Hd}+r)$. By dropping all the handoff calls and dropping max $(max(0, N-F), X(D_H+H)-D_N)$ then $\frac{D'_H}{D'_N} \leq \frac{1}{X}$ and either $\frac{D'_H+1}{D'_N} > \frac{1}{X}$, or $\frac{D'_H+1}{D'_N}$ is as large as possible. If $N_b = X(D_H+H)-D_N$, then $\frac{D'_H}{D'_N} = \frac{D_H+H}{D_N+X(D_H+H)-D_N} = \frac{1}{X}$. Therefore, $\frac{D'_H+1}{D'_N} > \frac{1}{X}$. If $N_b = max(0, N-F)$, *i.e.*, $X(D_H+H)-D_N < max(0, N-$

F). Therefore, $\frac{D'_H}{D'_N} = \frac{D_H+H}{D_N+max(0,N-F)} \le \frac{1}{X}$. However, $\frac{D'_H+1}{D'_N} = \frac{D_H+H+1}{D_N+max(0,N-F)}$ may be less than $\frac{1}{X}$, but has the maximum possible value. This is because in order to make $\frac{D'_H+1}{D'_N}$ larger there are two possibilities: either (D'_H+1) should increase which is impossible since all handoff calls are dropped, or D'_N should decrease which is also impossible since the maximum possible number of new calls were accepted. $\square$

It is possible that the procedure can not drop M_{Hd} handoff calls or N_b new calls, in such cases the procedure makes the dropping ratio to close as possible to the target range. This is shown in Lemma 3.4 and Lemma 3.5.

Lemma 3.4. *Let $H < M_{Hd}$ and suppose $\frac{D_H}{D_N}$ falls in the target range. Then $\frac{D'_H}{D'_N} \le \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.*

Proof. In this case, $H < M_{Hd} = \lfloor \frac{N+H-F}{X+1} \rfloor \le \frac{N+H-F}{X+1}$. Therefore, $XH \le (N-F)$. Thus, $\frac{H}{N-F} \le \frac{1}{X}$. By Lemma 3.2, since $\frac{D_H}{D_N} \le \frac{1}{X}$ and $\frac{H}{N-F} \le \frac{1}{X}$, we have $\frac{D'_H}{D'_N} = \frac{D_H+H}{D_N+N-F} \le \frac{1}{X}$. However, $\frac{D'_H+1}{D'_N} = \frac{D_H+H+1}{D_N+N-F}$ may be less than $\frac{1}{X}$, but has the maximum possible value. This is because in order to make $\frac{D'_H+1}{D'_N}$ larger there are two possibilities: either (D'_H+1) should increase which is impossible since all handoff calls are dropped, or D'_N should decrease which is also impossible since the maximum possible number of new calls were accepted. $\square$

Lemma 3.5. *Let $N < N_b$ and suppose $\frac{D_H}{D_N}$ falls in the target range. Then $\frac{D'_H+1}{D'_N} \ge \frac{1}{X}$ and $\frac{D'_H}{D'_N}$ is as small as possible.*

Proof. In this case, $N < N_b$, *i.e.* , $N \le N_b - 1 = N + H - F - (M_{Hd}+1)$. In other words, $H - F \ge M_{Hd} + 1 \ge \frac{N+H-F}{X+1}$. Therefore, $X(H-F) \ge N$. Thus, $\frac{H-F}{N} \ge \frac{1}{X}$. By Lemma 3.2, if $\frac{D_H+1}{D_N} \ge \frac{1}{X}$ and $\frac{H-F}{N} \ge \frac{1}{X}$, then $\frac{D_H+H-F+1}{D_N+N} \ge \frac{1}{X}$, *i.e.*, $\frac{D'_H+1}{D'_N} \ge \frac{1}{X}$. However, $\frac{D'_H}{D'_N}$ may be greater than $\frac{1}{X}$, but has the minimum possible value. This is because in order to make $\frac{D'_H}{D'_N}$ smaller either D'_H has to decrease which is impossible since the maximum possible number of handoff calls were accepted, or D'_N has to increase which is also impossible since all new calls were blocked. $\square$

3.1.2 GetInToTargetRange Procedure

In this section, we describe the procedure used in the case that the current dropping ratio falls out of the target range. The aim of the *GetInToTargetRange* procedure is to get the dropping ratio to fall in the target range as much as possible, regardless of the number of calls that can be accepted. In other words, in some situations some calls may be dropped even though free channels are available. For example, if the total number of calls requesting service ($N+H$) is less than the total free available channels F and the dropping ratio $\frac{D_H}{D_N}$ is greater than $\frac{1}{X}$, then the procedure will drop a certain amount of new calls in order to get $\frac{D'_H}{D'_N}$ to be exactly $\frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ to be greater than $\frac{1}{X}$. We present the key idea of the procedure here. Note that the dropping ratio falls out of the target dropping ratio if $\frac{D_H}{D_N} > \frac{1}{X}$ or if $\frac{D_H+1}{D_N} < \frac{1}{X}$. If $\frac{D_H}{D_N} > \frac{1}{X}$ we calculate N_b to be the number of new calls calls to be blocked. If the actual number of new calls is less than N_b we simply drop all new calls. Similarly, if $\frac{D_H+1}{D_N} < \frac{1}{X}$ we calculate H_d to be the number of handoff calls to be dropped. If the actual number of handoff calls is less than H_d, we simply drop all handoff calls. The pseudocode of the *GetInToTargetRange* procedure is presented in Figure 3.3. Theorem 3.2 shows that *GetInToTargetRange* procedure attempts to get the dropping ratio to fall in the target range as much as possible.

Theorem 3.2. *Let the current dropping ratio fall out of the target range. Then the GetInToTargetRange procedure gets the new dropping ratio as close to $\frac{1}{X}$ as possible.*

Proof. Let $N_b = \min\ (XD_H - D_N, N)$ and $H_d = \min\ (\lceil \frac{D_N - X(D_H+1)}{X} \rceil, H)$. If the current dropping ratio falls out of the target range, then four cases can occur:

1. $\frac{D_H}{D_N} > \frac{1}{X}$ and $N_b = N$. In this case, Lemma 3.6 proves that $\frac{D'_H+1}{D'_N} > \frac{1}{X}$ and $\frac{D'_H}{D'_N}$ is as small as possible.

2. $\frac{D_H}{D_N} > \frac{1}{X}$ and $N_b < N$. In this case, Lemma 3.7 proves that the new dropping ratio is as close as possible to the target range.

3. $\frac{D_H+1}{D_N} < \frac{1}{X}$ and $H_d = H$. In this case, Lemma 3.8 proves that $\frac{D'_H}{D'_N} < \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.

4. $\frac{D_H+1}{D_N} < \frac{1}{X}$ and $H_d < H$. In this case, Lemma 3.9 proves that the new dropping ratio is as close as possible to the target range.

$\square$

```
// pre-condition D_H/D_N > 1/X or (D_H+1)/D_N < 1/X
GetInToTargetRange (int H, int N, int F, int D_H, int D_N)
    { 1. if (D_H/D_N > 1/X)
        { N_b = min (X D_H − D_N, N)
        1.1 If N_b = N
            {H_d = max(H − F, 0)
            D'_H = D_H + max(H − F, 0)
            D'_N = D_N + N }
        1.2 else
            { // in this case, N_b < N)
            H_d = 0
            D'_H = D_H
            D'_N = D_N + N_b
            1.2.1 if (H + N − N_b) ≤ F)
                { Accept all remaining calls
                }
            1.2.2 else
                { // In this case, ((H + N − N_b) > F)
                MaintainTheRatio(H, N − N_b, F, D'_H, D'_N) }
            }
        }
    2. else
        { // In this case, ((D_H+1)/D_N < 1/X)
        { H_d = min (⌈(D_N − (D_H+1)·X)/X⌉, H)
        2.1 If (H_d = H)
            { N_b = max(N − F, 0)
            D'_H = D_H + H
            D'_N = D_N + N_b }
        2.2 else
            { //In this case, H_d < H)

            N_b = 0
            D'_H = D_H + H_d
            D'_N = D_N
            2.2.1 if(H − H_d + N) ≤ F)
                { Accept all remaining calls
                }
            2.2.2 else
                {//In this case, (H − H_d + N) > F)
                MaintainTheRatio (H − H_d, N, F, D'_H, D'_N) }
            }
        }
    }
```

Figure 3.3: The pseudocode of the *GetInToTargetRange* procedure

Lemma 3.6 and Lemma 3.7 assure that if $\frac{D_H}{D_N} > \frac{1}{X}$, then the procedure tries to make the ratio to be within the target range by dropping a suitable number of new calls such that $\frac{D'_H}{D'_N}$ is as small as possible. The number of new calls to be blocked N_b is min $(XD_H - D_N, N)$.

Lemma 3.6. *Let $N < XD_H - D_N$ and $\frac{D_H}{D_N} > \frac{1}{X}$. Then $\frac{D'_H+1}{D'_N} > \frac{1}{X}$ and $\frac{D'_H}{D'_N}$ is as small as possible.*

Proof. In this case, $D'_H = D_H +$ max $(H - F, 0)$ and $D'_N = D_N + N$. Since $N < (XD_H - D_N)$, we have $\frac{D_H}{D_N+N} > \frac{1}{X}$. Therefore, $\frac{D'_H}{D'_N} = \frac{D_H+max(H-F,0)}{D_N+N} \geq \frac{D_H}{D_N+N} > \frac{1}{X}$. Furthermore, this is the minimum value possible for $\frac{D'_H}{D'_N}$, as in order to have a smaller value, either D'_H has to decrease which is impossible since the maximum possible number of handoff calls were accepted, or D'_N has to increase which is also impossible since all new calls were blocked. □

Lemma 3.7. *Let $N \geq XD_H - D_N$ and $\frac{D_H}{D_N} > \frac{1}{X}$. Then $\frac{D'_H}{D'_N} \leq \frac{1}{X}$, or as small as possible, and $\frac{D'_H+1}{D'_N} \geq \frac{1}{X}$, or as large as possible.*

Proof. In this case, $N_b = XD_H - D_N$. Then $\frac{D'_H}{D'_N} = \frac{D_H}{D_N+N_b} = \frac{D_H}{D_N+XD_H-D_N} = \frac{1}{X}$. If $\frac{D'_H}{D'_N} = \frac{1}{X}$, then $\frac{D'_H+1}{D'_N} > \frac{1}{X}$ and the new dropping ratio falls in the target range. After dropping N_b new calls, the dropping ratio falls in the target range and all the remaining calls will be served if there are enough free channels. Otherwise, the *GetInToTargetRange* procedure calls *MaintainTheRatio* to drop handoff calls to new calls with $\frac{1}{X}$ ratio. The result then follows from Theorem 3.1. □

Lemma 3.8 and Lemma 3.9 assure that if $\frac{D_H+1}{D_N} < \frac{1}{X}$, then the procedure tries to drop a suitable number of handoff calls such that $\frac{D'_H+1}{D'_N}$ is as large as possible. The number of handoff calls to be dropped H_d is min $(\lceil\frac{D_N-X(D_H+1)}{X}\rceil, H)$.

Lemma 3.8. *Let $H < \lceil\frac{D_N-X(D_H+1)}{X}\rceil$ and $\frac{D_H+1}{D_N} < \frac{1}{X}$. Then $\frac{D'_H}{D'_N} < \frac{1}{X}$ and $\frac{D'_H+1}{D'_N}$ is as large as possible.*

Proof. In this case, Let $D'_H = D_H + H$ and $D'_N = D_N+$max $(N - F, 0)$. Since $H < \lceil\frac{D_N-X(D_H+1)}{X}\rceil$, we have $\frac{D_H+H+1}{D_N} < \frac{1}{X}$. Therefore,

$$\frac{D'_H+1}{D'_N} = \frac{D_H+H+1}{D_N+max(N-F,0)} \leq \frac{D_H+H+1}{D_N} < \frac{1}{X}.$$

Furthermore, this is the maximum value possible for $\frac{D'_H+1}{D'_N}$, as in order to have a larger value, either (D'_H+1) has to increase which is impossible since all handoff calls were dropped, or D'_N has to decrease which is also impossible since the maximum possible number of new calls were accepted. $\square$

Lemma 3.9. *Let $H \geq \lceil \frac{D_N - X(D_H+1)}{X} \rceil$ and $\frac{D_H+1}{D_N} < \frac{1}{X}$. Then $\frac{D'_H}{D'_N} \leq \frac{1}{X}$, or as small as possible, and $\frac{D'_H+1}{D'_N} \geq \frac{1}{X}$, or as large as possible.*

Proof. In this case, $H_d = \lceil \frac{D_N - X(D_H+1)}{X} \rceil$. Then, $\frac{D'_H}{D'_N} = \frac{D_H+H_d}{D_N} \leq \frac{D_H + \lceil \frac{D_N - X(D_H+1)}{X} \rceil + 1}{D_N}$ $\leq \frac{XD_H + D_N - XD_H - X + X}{XD_N} = \frac{1}{X}$.
Also, $\frac{D'_H+1}{D'_N} = \frac{D_H+H_d+1}{D_N} \geq \frac{D_H + \lceil \frac{(D_N - X(D_H+1)}{X} \rceil + 1}{D_N} \geq \frac{D_H + D_N - XD_H - X + X}{XD_N} = \frac{1}{X}$. Since $\frac{D'_H}{D'_N} \leq \frac{1}{X}$ and $\frac{D'_H+1}{D'_N} \geq \frac{1}{X}$, the new dropping ratio falls in the target range.
After dropping H_d handoff calls, the dropping ratio falls in the target range and all the remaining calls will be served if there are enough free channels. Otherwise, the *GetInToTargetRange* procedure calls *MaintainTheRatio* to drop handoff calls to new calls with a $\frac{1}{X}$ ratio. The result then follows from Theorem 3.1. $\square$

3.1.3 Performance of MR Algorithm

In order to study the performance of the MR algorithm, several computational experiments were carried out for different new call arrival rates. The performance of the MR algorithm certainly depends on the value of the dropping ratio $\frac{1}{X}$. In particular, as the new call arrival rate increases, the value of X that produces a minimum GoS also increases. The performance of the MR algorithm using the best value of X for each new call arrival rate is compared with the performance of Fixed Channel Assignment (FCA), Fixed Channel Assignment giving Handoff Priority (FCAHP), Fixed Preference Assignment (FPA), Fixed Threshold Assignment (FTA), and Adaptive Threshold Assignment (ATA). Except FPA all channel assignment algorithms disallow borrowing of channels. A summary of the simulation parameters used in the computational experiments is given in Table 3.1.

Figure 3.4 compares the GoS of the MR algorithm with other channel assignment algorithms. The performance of the MR algorithm is better than FCA, FCAHP and

Parameter	Variable	Value(s)
Channels / cell	C	7
New call arrival rate	λ	0.02 -0.05 calls/sec/cell
Cell radius	R	1000 m
Average mean speed	v	0.01 R/sec
Mean call duration	T_M	120 sec
Dropping probability weightage factor	α	10

Table 3.1: Simulation Parameters

FPA. However, FTA and ATA outperform the MR algorithm for all new call arrival rates. In order to investigate the reasons that FTA and ATA outperform MR, P_N and P_H for FTA and ATA are compared with P_N and P_H for MR for different values of X and illustrated in Figures 3.5 and 3.6.

As shown in Figures 3.5 and 3.6, the value of P_N and P_H for MR depends on the values of X. As X increases, the probability of blocking increases and probability of dropping decreases. As indicated in Figure 3.6, the probability of dropping for FTA is more or less the same as that for MR when X is 24. However, as shown in Figure 3.5, the probability of blocking for MR when X is 24 is higher than that for FTA. The reason that FTA outperforms MR is that the probability of blocking for MR is much higher than that for FTA when both algorithms have almost the same probability of dropping. Figures 3.5 and 3.6 also show that ATA has the lowest P_H value over all new call arrival rates while FTA has the lowest P_N value over all new call arrival rates. One can speculate that by decreasing the value of X, P_N would decrease. This is true, though there is a direct relation between P_N and P_H since $XD_H \leq D_N \leq (X+1)D_H$ and $\frac{XD_H}{N} \leq P_N \leq \frac{(X+1)D_H}{N}$. If X is decreased then P_N will decrease by a small amount almost equal to $\frac{D_H}{N}$.

Another indication of the system performance that we are interested in, in this thesis, is the non-completed call probability P_{ns} that was defined in Chapter 2. P_{ns} measures the probability that a call is not completed due to blocking of a new call or dropping of a handoff call. In other words, P_{ns} does not prioritize handoff call requests over new call requests. Figure 3.8 compares the P_{ns} of the MR algorithm with other channel assignment algorithms. As shown in Figure 3.7 and Figure 3.8,

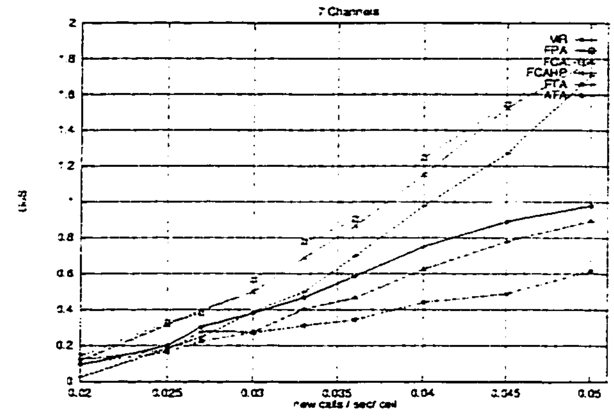

Figure 3.4: Effect of new call arrival rate on GoS for different channel assignment algorithms.

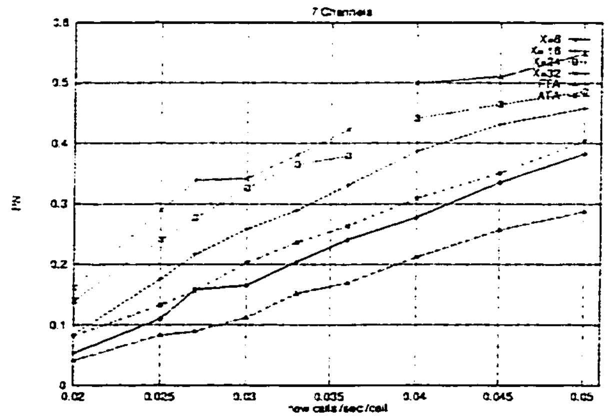

Figure 3.5: Effect of new call arrival rate on P_N for FTA, ATA, and MR for different values of X.

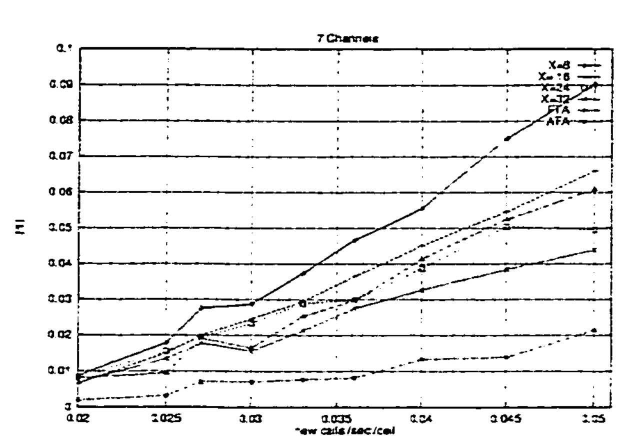

Figure 3.6: Effect of new call arrival rate on P_H for FTA, ATA, and MR for different values of X.

FCA, FCAHP, and FPA have more or less the same P_{ns} and channel non-utilization which are better than those of MR, FTA, and ATA. This is due to the fact that FCA, FCAHP, and FPA do not reserve channels for handoff calls for the future but they serve new call requests if free channels are available. These findings motivated us to devise some modifications to the MR algorithm to avoid dropping new calls unnecessarily.

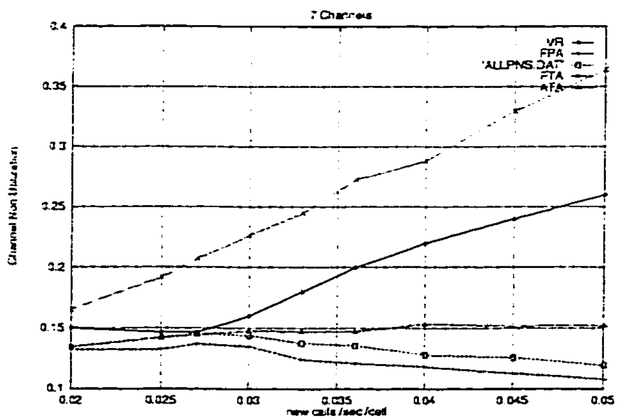

Figure 3.7: Effect of new call arrival rate on channel non-utilization for different channel assignment algorithms.

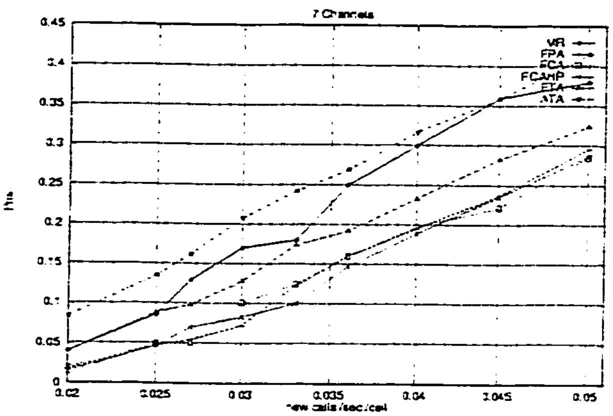

Figure 3.8: Effect of new call arrival rate on P_{ns} for different channel assignment algorithms.

3.2 The LR Algorithm

The LR algorithm is a simple modified version of the MR algorithm. The aim of the LR algorithm is to improve the performance of the MR algorithm by giving new calls a higher chance to be served if there are free channels. The fundamental idea of the MR algorithm is also preserved in the LR algorithm. However, we additionally use the guard channel concept in this algorithm. For the sake of simplifying the algorithm, LR aims to get the dropping ratio to be *less than or equal to a predefined target ratio* rather than getting it in a target range. As in the MR algorithm, the LR algorithm is divided into two cases. The first case is when the dropping ratio is less than or exactly equal to the target ratio, while the second case is when the dropping ratio is greater than the target ratio. In the first case, the algorithm calls *MaintainTheRatio* procedure to find the number of calls to be dropped in order to maintain the dropping ratio. However, in the second case, *MakeRatioLessThanTarget* procedure is called trying to get the dropping ratio to be less than or exactly equal to the target ratio as much as possible. The *MaintainTheRatio* procedure is exactly the same as *MaintainTheRatio* in the MR algorithm.The pseudocode of the LR algorithm is shown in Figure 3.9. The aim of the LR algorithm is to keep the number of new calls dropped, D_N, is at most XD_H, *i.e.*, the target ratio is given by:

$$XD_H \leq D_N$$

$$\frac{D_H}{D_N} \le \frac{1}{X} \tag{3}$$

As in the case of the MR algorithm, the aim cannot always be met for arbitrary traffic conditions. For example, if $\frac{D_H}{D_N} = \frac{1}{X}$ and only handoff calls are received in the next steps, then D_H may increase, while D_N cannot change, thus causing the dropping ratio to become larger than the target ratio. In what follows we prove that even under arbitrary traffic conditions the algorithm tries to keep the dropping ratio below the target ratio as much as possible. In some cases, however, because of the use of the guard channel, we can not accomplish the best possible value of dropping ratio, but merely improve on the previous value, thus establishing that some progress is made toward the goal.

```
The LR Algorithm (int H, int N, int F, int D_H, int D_N)
    {
    if D_H/D_N <= 1/X
      {
      If (N + H) <= F
        { Accept all calls
        }
      else
        { MaintainTheRatio(H, N, F, D_H, D_N)
        }
      }
    else
      { // In this case, D_H/D_N > 1/X
      MakeRatioLessThanTarget(H, N, F, D_H, D_N)
      }
    }// end of the LR Algorithm
```

Figure 3.9: The pseudocode of the *LR* algorithm

The pseudocode of the *MakeRatioLessThanTarget* is presented in Figure 3.10. The *MakeRatioLessThanTarget* procedure attempts to improve the dropping ratio and gets it closer to the target ratio. The *MakeRatioLessThanTarget* procedure is divided into two cases. In the first case, there are enough channels to serve all handoff calls whereas in the second case the total number of handoff calls requesting service is greater than the available free channels. In the first case, the total number of handoff calls dropped D'_H will remain the same as D_H and the total number of new call blocked D'_N will

```
// pre-condition D_H/D_N > 1/X
MakeRatioLessThanTarget (int H, int N, int F, int D_H, int D_N)
                  { 1. If H ≤ F
                        {// accept all handoff calls and all possible new calls except one guard channel.
                        H_d = 0
                        N_b = max (N - (F - H - 1), 0)
                        D'_H = D_H
                        D'_N = D_N + N_b
                        }
                  }
                  2. else
                      { // In this case, H > F
                      H_d = H - F
                      N_b = N
                      D'_H = D_H + H_d
                      D'_N = D_N + N_b
                      }
                  }
```

Figure 3.10: The pseudocode of the *MakeRatioLessThanTarget* procedure

increase. Theorem 3.3 shows that *MakeRatioLessThanTarget* procedure attempts to get the dropping ratio to be less than or equal to the target ratio as much as possible.

Theorem 3.3. *Let $\frac{D_H}{D_N}$ be greater than $\frac{1}{X}$. Then the MakeRatioLessThanTarget procedure makes the new dropping ratio smaller than $\frac{1}{X}$ as much as possible.*

Proof. In this case, $\frac{D_H}{D_N} > \frac{1}{X}$, then three cases could occur:

1. $H \leq F$ and $N_b \geq XD_H - D_N$. In this case, Lemma 3.10 proves that the $\frac{D_H}{D_N} \leq \frac{1}{X}$.

2. $H \leq F$ and $N_b < XD_H - D_N$. In this case, Lemma 3.11 proves that the new dropping ratio $\frac{D_H}{D_N} > \frac{D'_H}{D'_N} > \frac{1}{X}$. Thus, the new dropping ratio has been improved.

3. $H > F$. In this case, Lemma 3.12 proves that the new dropping ratio is as small as possible.

□

Lemmas 3.10 and 3.11 deal with the first two cases in the theorem where all handoff calls are accepted.

Lemma 3.10. *Let $H \leq F$. Then by accepting all handoff calls and as many new calls as possible such that at least one channel will remain free while blocking at least $XD_H - D_N$ new calls, the new dropping ratio is at most equal to $\frac{1}{X}$.*

Proof. In this case, $H_d = 0$ and $N_b \geq XD_H - D_N$. Therefore, $\frac{D'_H}{D'_N} \leq \frac{D_H}{D_N + XD_H - D_N} = \frac{1}{X}$ and the new dropping ratio is at most equal to the target ratio. □

Lemma 3.11. *Let $H \leq F$. Then by accepting all handoff calls and as many new calls as possible such that at least one channel will remain free while blocking less than $XD_H - D_N$ new calls, results in $\frac{D'_H}{D'_N}$ being closer to $\frac{1}{X}$ than $\frac{D_H}{D_N}$.*

Proof. In this case, $H_d = 0$ and $N_b < XD_H - D_N$. Then $\frac{D'_H}{D'_N} > \frac{D_H}{D_N + XD_H - D_N}$. Thus, $\frac{D'_H}{D'_N} > \frac{1}{X}$. However, since $D'_H = D_H$ and $D'_N > D_N$ we have $\frac{D_H}{D_N} > \frac{D'_H}{D'_N} > \frac{1}{X}$. Therefore, the dropping ratio has been improved.

□

Lemma 3.12 shows that if the third case occurs, then the procedure can only accept some of the handoff calls and drop all new calls and this makes the new dropping ratio $\frac{D'_H}{D'_N}$ as small as possible.

Lemma 3.12. *Let $H > F$ and $\frac{D_H}{D_N} > \frac{1}{X}$. Then accepting F handoff calls and dropping all new calls results in $\frac{D'_H}{D'_N}$ being as small as possible.*

Proof. In this case, $D'_H = D_H + H - F$ and $D'_N = D_N + N$. Then $D'_H > D_H$ and $D'_N > D_N$. In order to make $\frac{D'_H}{D'_N}$ smaller either D'_H has to decrease which is impossible since the maximum possible number of handoff calls were accepted, or D'_N has to increase which is also impossible since all new calls were blocked. Thus $\frac{D'_H}{D'_N}$ is as small as possible. □

3.2.1 Performance of the LR Algorithm

In this section, we compare the performance of the LR algorithm with the performance of FTA and ATA for different new call arrival rates. Figure 3.11 illustrates the effect of new call arrival rates between 0.02 -0.05 calls/sec/cell on GoS for LR, FTA, and ATA .

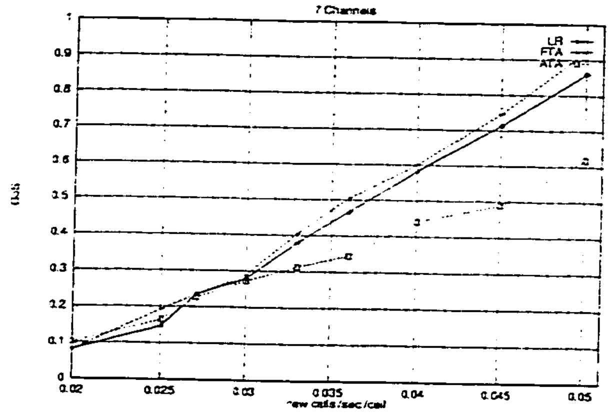

Figure 3.11: Effect of new call arrival rate on GoS for LR, FTA, and ATA.

The GoS of LR and FTA as shown in Figure 3.11 are more or less the same. The ATA algorithm has the lowest GoS when the call arrival rate is greater than 0.03 calls/sec/cell. Figures 3.12 to 3.15 illustrate the probability of blocking new calls, the probability of dropping handoff calls, the channel utilization, and the non-completed call probability P_{ns} for LR, FTA, and ATA, respectively.

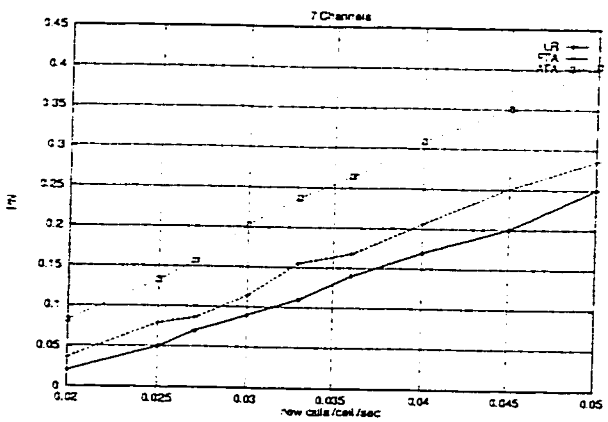

Figure 3.12: Effect of new call arrival rate on P_N for LR, FTA, and ATA.

As shown in Figure 3.12 and Figure 3.14, the LR algorithm has lowest blocking probability and almost the same channel non-utilization as ATA. A comparison between the P_{ns} of the three algorithms is shown in Figure 3.15. Although ATA reduces

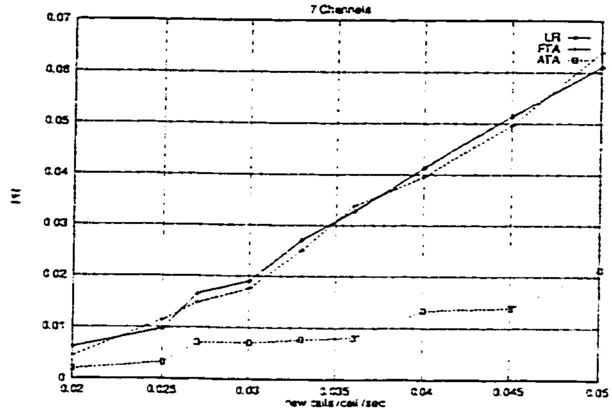

Figure 3.13: Effect of new call arrival rate on P_H for LR, FTA, and ATA.

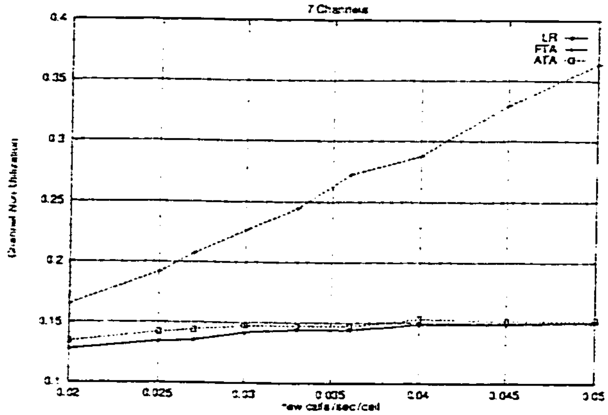

Figure 3.14: Effect of new call arrival rate on channel non-utilization for LR, FTA, and ATA.

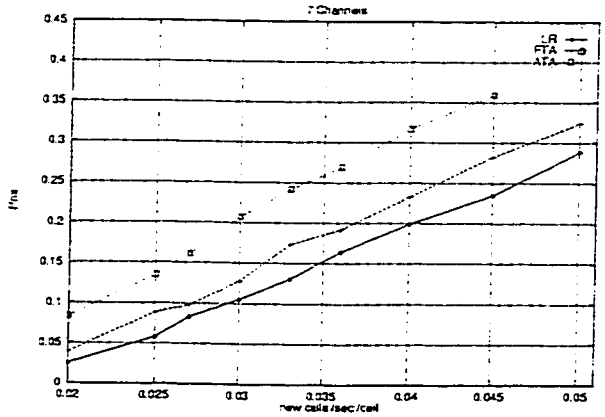

Figure 3.15: Effect of new call arrival rate on P_{ns} for LR, FTA, and ATA.

the handoff failure probability, it increases the blocking of new calls which in turn increases the non-completed call probability P_{ns}. Comparing Figure 3.8 and Figure 3.15, the LR algorithm has almost the same P_{ns} as FCA, FCAHP, and FPA. Our algorithm balances between minimizing the GoS and minimizing the P_{ns}. The LR algorithm also achieves the best channel non-utilization under various traffic loads. The behavior of the LR algorithm is discussed in greater detail in Chapter 4.

Chapter 4

Computational Experiments

In order to study the behaviour of the MR and the LR algorithms, several computational experiments were carried out, the results of which are reported in this chapter. These experiments were run to investigate the effect of changing cellular network parameters such as the new call arrival rate, cell radius, mobile terminal speed, and mobile call duration on the blocking and the dropping probabilities. Traffic load in cellular networks is heavily dependent on these parameters. The new call arrival rates are the main source of load on the cellular networks, while the mobile terminal speed, the mobile call duration, and the cell radius determine the duration a channel will be occupied in a cell and the number of handoffs during a call session. The effect of changing the target dropping ratio is also studied. The target dropping ratio $\frac{1}{X}$ has a direct effect on the number of handoff calls dropped and the number of new calls blocked which in turn affects both the dropping and the blocking probabilities.

In Section 4.3 the performance of the LR algorithm is compared with the performance of the FTA and ATA algorithms. The performance of the three algorithms is evaluated in terms of the GoS, P_{ns}, and γ.

4.1 Base Problem

In order to prepare the problem sets for comparison, a sample problem was chosen as the base problem. The system parameter values of this base problem are chosen such that they resemble real life cases. Although some of the parameters may be over- or underestimated, we aimed to make pessimistic choices where necessary. Hence the performance of the system is supposed to be better in the real life cases.

In the majority of cellular network design studies, several assumptions are necessary for calculating the performance of the system in a reasonable time. Figure 4.1 shows the structure of the cellular network used in our simulations with 49 cells. The network cells can be classified as one of two types: either *edge cells* for which the set of interference is incomplete, or *central cells* for which the set of interfering cells is complete (shaded cells in Figure 4.1). All our statistical results are collected from the central cells.

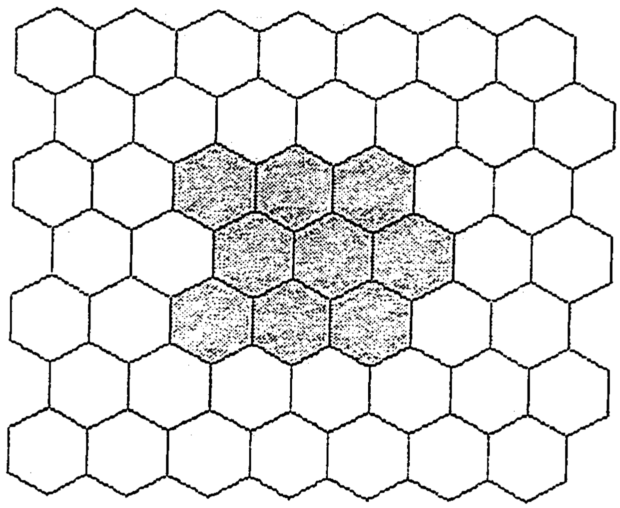

Figure 4.1: Cellular Network

We made several simplifying assumptions in our work. The first assumption is about the *call inter-arrival rate* which is the time between the creation of two mobile calls. The call inter-arrival rate is assumed to be exponentially distributed with a mean $1/\lambda$. The *mean call duration* (T_M) is the time until a call terminates which is assumed to be exponentially distributed with a mean $1/\mu$. Furthermore, it is assumed that mobile terminals move with a constant speed v_{mean} to any neighboring cells with equal probability.

A summary of the simulation parameters used in this thesis is given in Table 4.1.

Each simulation is allowed a warm-up period of 200 sec before results and statistics are collected. The simulation duration is 10000 sec. The mean call arrival rate is 0.03 calls/sec/cell. This value corresponds to approximately 510000 calls in 24 hours in a city of size 500 km^2. The value for the cluster size is seven which correspond to a reuse distance of three. The total number of available channels in each cell is chosen to be 7. The mean speed of the mobile terminal is chosen to be 10 m/sec (36 km/h) which corresponds to the mean speed of a car in city traffic. Furthermore, the mean call duration is chosen as 120 seconds. This duration is rather short when compared with the mean call duration of conventional telephone services.

Parameter	Variable	Value(s)
Channels / cell	C	7
New call arrival rate per cell	λ	0.03 calls/sec/cell
Target dropping ratio	$\frac{1}{X}$	$\frac{1}{6}$ and $\frac{1}{8}$
Cell radius	R	1000 m
Average mean speed	v_{mean}	0.01R/sec
Mean call duration	T_M	120 sec
Dropping probability factor	α	10

Table 4.1: Parameters of the Base Problem

4.2 Validation

The performance of the simulator used in this thesis was first validated by running published algorithms using their system parameters. Results obtained from FCA, FTA, and ATA were compared with results published in the literature. However, results obtained from FCAHP and FPA were not validated since no such published data exists. The FCA algorithm was tested and then compared with the results obtained in [38] under the assumption of the same call arrival process with equal mean arrival rates (0.033-0.05 call/sec/cell) , equal number of channels assigned to each cell (7 channels/cell), equal mean speed (0.09R/s), and equal mean call duration (180 sec). Our simulator results obtained for FCA and the results in [38] were in good agreement. FTA and ATA were tested using our simulator and then compared with the results obtained in [35]. To obtain the results we have used the same assumptions used in [35]. For 7 channels/cell the new call arrival rate was assumed to be 0.0208 call/sec/cell. The call duration was assumed to be 120 sec and the average mobile speed was assumed to be 0.01R/s. Results obtained using our simulator were comparable to the results published in [35]. These experiments validate the performance of our simulator and give a reasonable expectation of the validity of our experimental results.

4.3 Effect of System Parameters

Performance analysis of various call admission algorithms is virtually impossible without running simulations. In this subsection, the effects of changing system parameters on the MR and LR algorithms are examined in detail. The results are presented as charts. Only one parameter is changed at a time. We are interested in studying the effect of changing system parameters on the total number of new call attempts (N), the total number of handoff calls attempts inside the network (H), the total number of handoff calls moving outside the network (H_{out}), the number of new calls blocked (D_N), and the number of handoffs dropped (D_H).

4.3.1 Effect of Target Dropping Ratio

The effect of changing the target dropping ratio ($\frac{1}{X}$) is examined in this section. Recall that the heuristic studied in this thesis is that X new calls should be dropped before dropping one handoff call. First we run experiments to see to what extent the MR and the LR procedures implement this heuristic. Figures 4.2 and 4.3 show $\frac{D_H}{D_N}$ for MR and LR respectively, with X varying from 1 to 30. Figure 4.2 shows that for the MR algorithm, the ratio of the number of handoff calls dropped to the number of new calls blocked ($\frac{D_H}{D_N}$) is always almost exactly $\frac{1}{X}$. Figure 4.3 shows that for the LR algorithm, the dropping ratio stays reasonably close to $\frac{1}{X}$ while not maintaining the exact value.

Figures 4.4 to 4.6 show the effect of changing the target dropping ratio on MR. In Figure 4.4, the new call arrival rate is kept fixed, and the value of X is changed. Note that N stays the same while both H and H_{out} decrease with increasing X. The

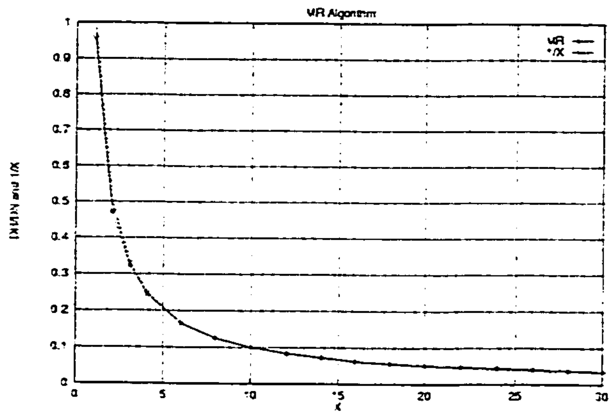

Figure 4.2: Effect of increasing the target dropping ratio $\frac{1}{X}$ on $\frac{D_H}{D_N}$ of the MR algorithm.

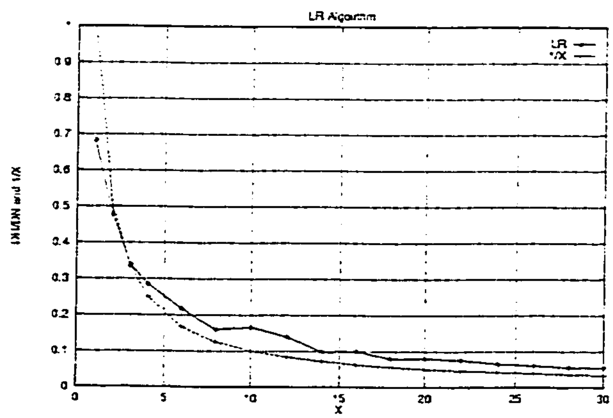

Figure 4.3: Effect of increasing the target dropping ratio $\frac{1}{X}$ on $\frac{D_H}{D_N}$ of the LR algorithm.

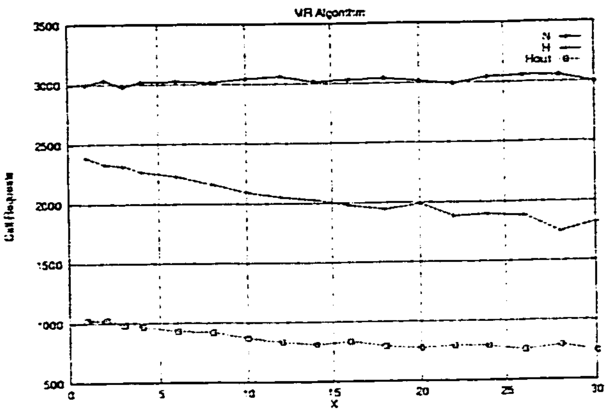

Figure 4.4: Effect of increasing the target dropping ratio $\frac{1}{X}$ on N, H, and H_{out} for the MR algorithm.

explanation for this can be found in Figure 4.5, which shows that as X increases, the number of new calls blocked, D_N, increases. The number of handoff call attempts, H, decreases since the number of admitted calls decreases with increasing X. Since H decreases, H_{out} decreases as well. Figure 4.5 also shows that D_H decreases with increasing X: this is to be expected since X new calls are dropped before dropping one handoff call.

Figure 4.6 shows the effect of increasing X on the blocking probability (P_N) and the dropping probability (P_H). Since N is constant, P_N has the same curve as D_N; but the rate of the decrease in P_H is slower than the rate of the decrease in D_H. This is because the rate of the decrease in H is faster than the rate of decrease in D_H.

Figures 4.7 to 4.9 show the effect of changing the target dropping ratio on LR. In Figure 4.7, N, H, and H_{out} are almost constant. In Figures 4.8 and 4.9, D_N and P_N are increasing, while D_H and P_H are decreasing. The number of new calls dropped is increasing slowly due to the fact that LR accepts new calls if there are free channels. Therefore, the number of handoff call attempts is almost constant. Since N is constant, D_N and P_N should follow the same curve. Also, since H is almost constant and D_H is decreasing, D_H and P_H follow the same curve.

Both algorithms have similar behaviour, except that the number of handoff call attempts H for the LR algorithm is almost constant, while it is decreasing for the MR algorithm. This shows that LR accepts more new calls compared to MR, as expected.

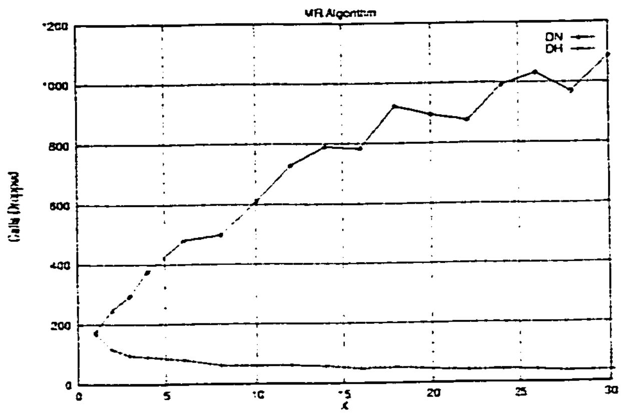

Figure 4.5: Effect of increasing the target dropping ratio $\frac{1}{X}$ on D_N, and D_H for the MR algorithm.

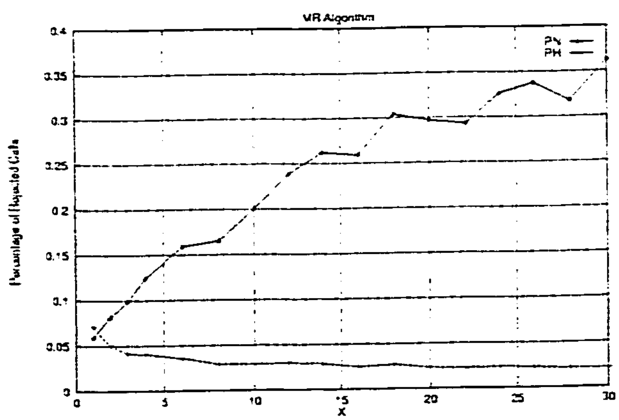

Figure 4.6: Effect of increasing the target dropping ratio $\frac{1}{X}$ on P_N, and P_H for the MR algorithm.

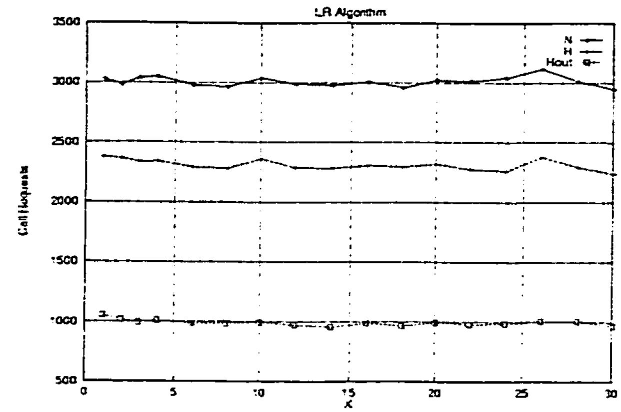

Figure 4.7: Effect of increasing the target dropping ratio $\frac{1}{X}$ on N, H, and H_{out} for the LR algorithm.

4.3.2 Effect of Call Arrival Rate

The effect of changing the call arrival rate is examined in this subsection. In subsequent experiments, the call arrival rate is increased from 0.02 to 0.05 calls per sec per cell. The results of MR with fixed dropping ratio indicate that as the call arrival rate increases, the number of handoff call attempts also increases (Figure 4.10) but with a lower rate compared to the rate of the increase of new calls. This is because with a mean call duration of 120 sec and an average mobile speed of 0.01R/s, the probability that a call in the current cell produces a handoff toward a neighboring cell P_h is less than 40%. This is calculated as follows: $P_h = \frac{1-e^{\beta}(1-\beta)}{2\beta} - \frac{\beta}{2}\int_{\beta}^{+\infty}\frac{e^{-x}}{x}\,dx$ where $\beta = \frac{R}{v_{mean}T_m}$ [38].

Using the best dropping ratio for different new call arrival rates helps to improve the system performance. Therefore, the effect of changing the target dropping ratio on a new call arrival rate range between 0.02 and 0.05 calls/sec/cell is also examined. As expected, for a higher X value, D_N is higher and D_H is lower, this fact is illustrated in Figure 4.11. In particular, D_N for a dropping factor $X = 4$ is less than D_N for a dropping factor $X = 12$, while D_H for a dropping factor $X = 4$ is greater than D_H for a dropping factor $X = 12$. Figure 4.12 illustrates that both the new call blocking

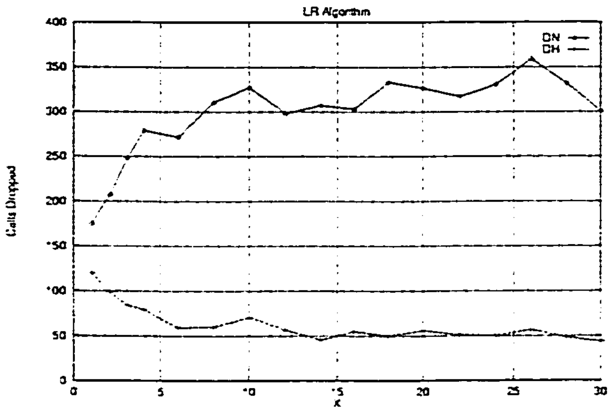

Figure 4.8: Effect of increasing the target dropping ratio $\frac{1}{X}$ on D_N, and D_H for the LR algorithm.

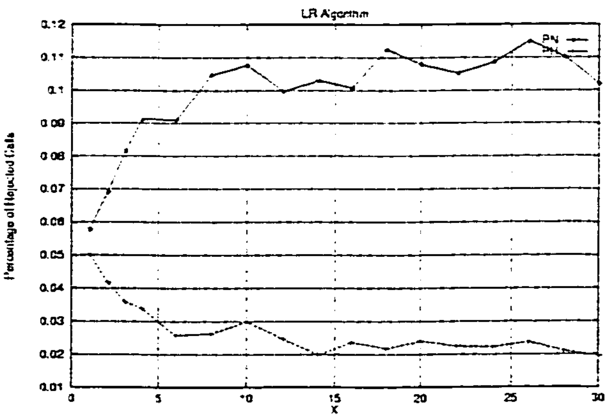

Figure 4.9: Effect of increasing the target dropping ratio $\frac{1}{X}$ on P_N, and P_H for the LR algorithm.

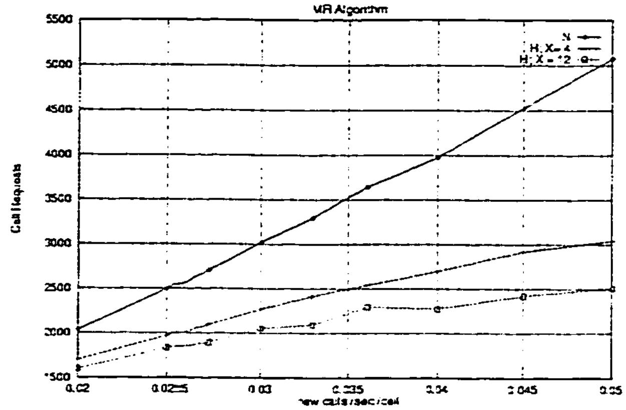

Figure 4.10: Effect of increasing the new call arrival rate on N, and H for the MR algorithm.

probability and the handoff dropping probability are increased as the new call arrival rate increases, for both values of X.

The effect of changing the new call arrival rate on the LR algorithm is presented in Figures 4.13 to 4.15. LR has the same behavior as MR except that in LR the difference between D_N when $X = 4$ and D_N when $X = 12$ is less than that in MR due to the fact that new calls have a higher chance to be served in LR than in MR.

4.3.3 Effect of Mean Speed

Another parameter to be examined is the mean speed of mobile terminals. The mean speed was divided into two classes: moderate mean speed class and high mean speed class. The moderate mean speed corresponds to a walking mobile user and a slow driving user in city traffic, while the high mean speed class corresponds to a user driving on low-traffic highways. In the moderate speed class the mean speed is increased from 0.002 R/s to 0.012 R/s, while in the high speed class the mean speed is increased from 0.01 R/s to 0.08 R/s. The results of the moderate mean speed class are presented in Figures 4.16 to 4.18 for the MR algorithm. Figure 4.16 shows that for a fixed call arrival rate and a fixed target dropping ratio, the number of handoff call attempts increases as the speed increases. This is entirely to be expected since a mobile terminal traveling at a high speed will cross more cell boundaries during

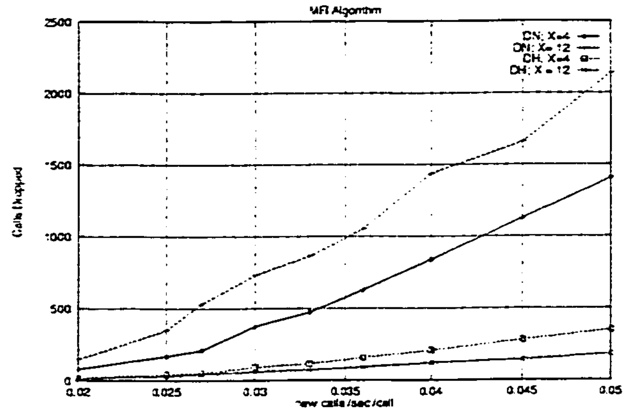

Figure 4.11: Effect of increasing the new call arrival rate on D_N, and D_H for the MR algorithm.

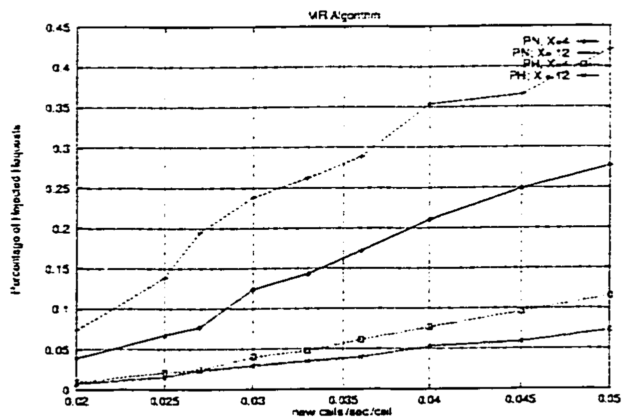

Figure 4.12: Effect of increasing the new call arrival rate on P_N, and P_H for the MR algorithm.

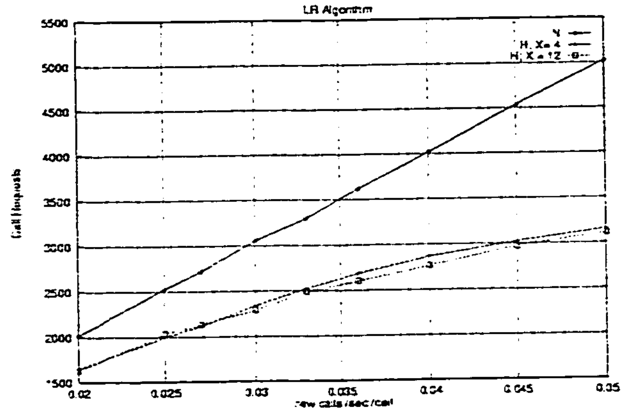

Figure 4.13: Effect of increasing the new call arrival rate on N, and H for the LR algorithm.

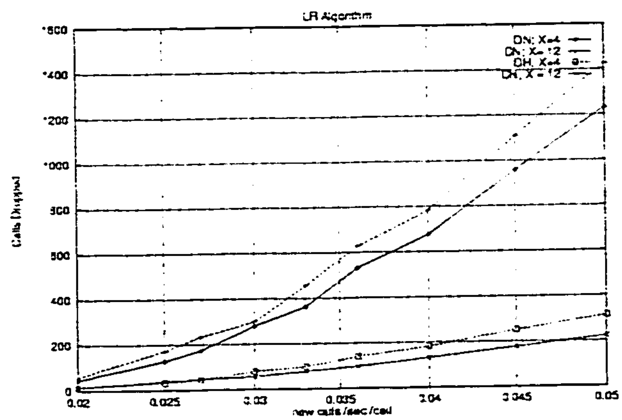

Figure 4.14: Effect of increasing the new call arrival rate on D_N, and D_H for the LR algorithm.

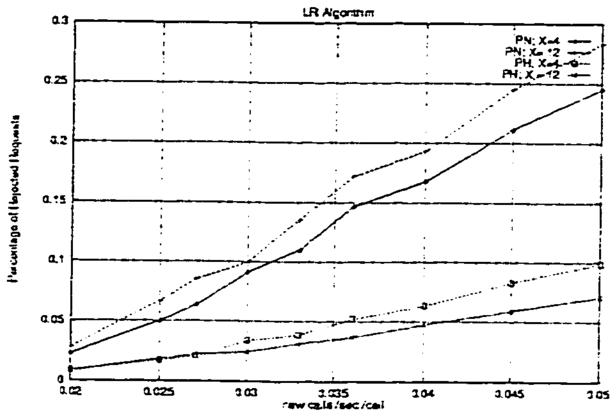

Figure 4.15: Effect of increasing the new call arrival rate on P_N, and P_H for the LR algorithm.

a fixed period than one traveling at a lower speed. Since the total number of calls requesting service is increased, more calls are blocked as well as dropped. Indeed Figure 4.17 shows that D_N and D_H increase with increasing speed. Figure 4.18 shows the effect of speed on P_N and P_H. The new call blocking probability increases since the new call arrival rate is constant and D_N is increasing. However, the handoff dropping probability decreases because the rate of the increase in the handoff call attempts is higher than the rate of the increase in the handoff calls dropped. The difference between the rate of increase in H and D_H can be explained as follows: since N is constant and H is increasing, the total number of calls requesting service $(N + H)$ increases. Therefore, the total number of calls to be dropped $(D_H + D_N)$ would also increase. However, X new calls are blocked before dropping one handoff call. Therefore, the rate of the increase in the handoff call attempts is higher than the rate of the increase in the handoff calls dropped. This also explains why D_N in Figure 4.17 increases with a higher rate than the increase in D_H. This fact is used extensively in the rest of this chapter.

The mean speeds of the high speed class are chosen to vary between 0.01 R/s (36 km/h) and 0.08 R/s (288 km/h). Although 0.08 R/s (288 Km/h) is an imaginary speed, we were interested in studying the effect of such high speed on the number of handoff calls attempts and the number of calls being handed-off outside the network. The results of the high mean speed class are presented in Figures 4.22 to 4.24. for

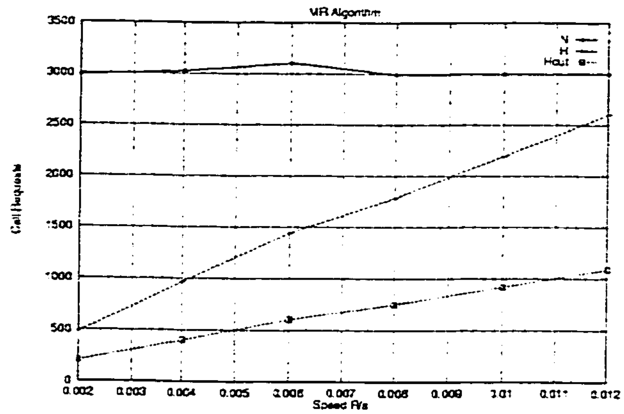

Figure 4.16: Effect of increasing the mean speed of the moderate speed class on N, H, and H_{out} for the MR algorithm.

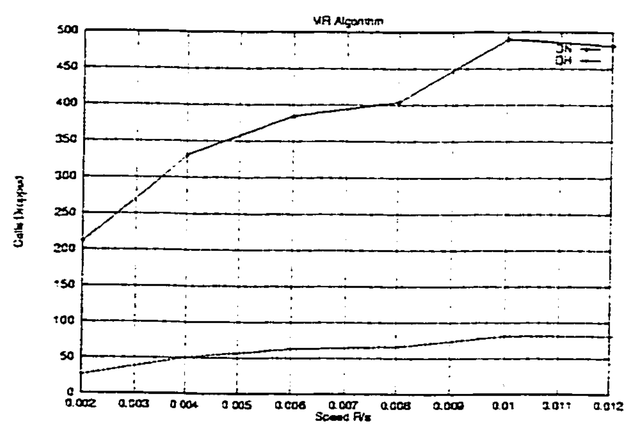

Figure 4.17: Effect of increasing the mean speed of the moderate speed class on D_N, and D_H for the MR algorithm.

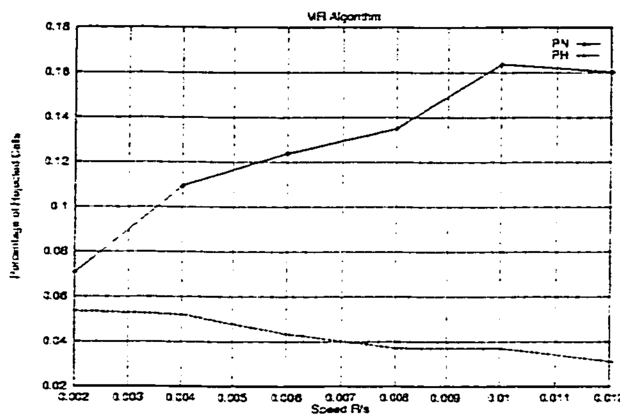

Figure 4.18: Effect of increasing the mean speed of the moderate speed class on P_N, and P_H for the MR algorithm.

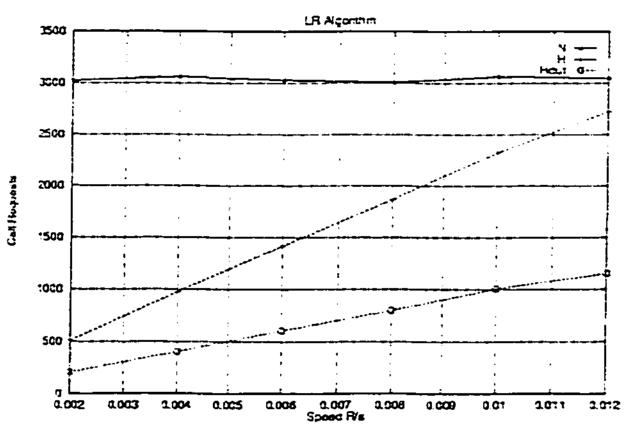

Figure 4.19: Effect of increasing the mean speed of the moderate speed class on N, H, and H_{out} for the LR algorithm.

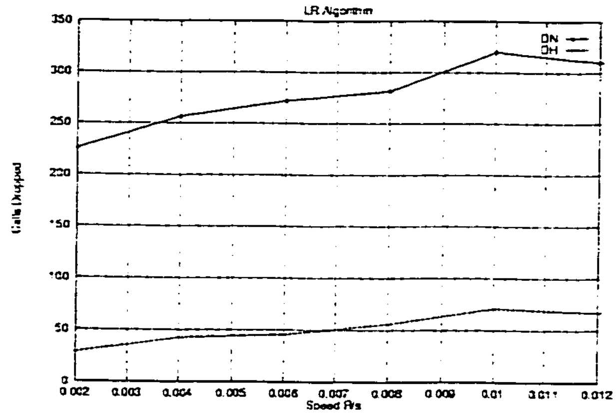

Figure 4.20: Effect of increasing the mean speed of the moderate speed class on D_N, and D_H for the LR algorithm.

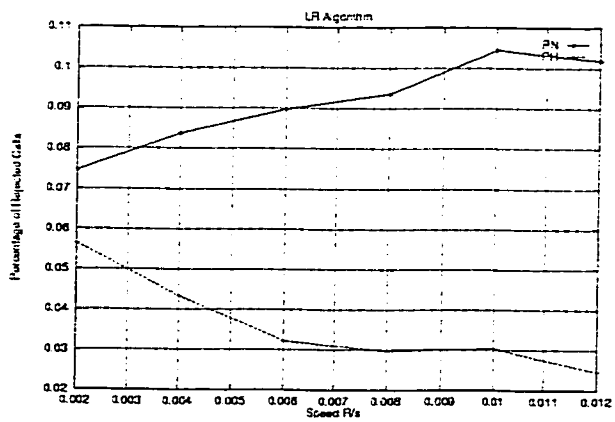

Figure 4.21: Effect of increasing the mean speed of the moderate speed class on P_N, and P_H for the LR algorithm.

the MR algorithm. In Figure 4.22, for a speed less than 0.02 R/s the handoff call attempts inside the network and the handoff calls moving outside the network are less than the new call requests. However, for a speed higher than 0.02R/s the number of handoff attempts is greater than the number of new call requests. For a speed higher than 0.04 R/s, the number of handoff calls moving outside the network H_{out} is greater than N.

In Figure 4.23, for a speed less than 0.02 R/s D_N and D_H increase. However, for a speed higher than 0.02 R/s D_N and D_H decrease sharply. This can be explained as follows: at lower speeds, the number of handoff call attempts (H) is rising sharply, while the number of calls moving outside the network is still not that high. Since the total number of admitted calls is increased, D_N as well as D_H increase. At higher speeds, the number of handoff calls moving outside the network H_{out} overwhelms the effect of the large number of handoffs. In other words, channels are more likely to be free. Thus, both D_N and D_H decrease.

Figure 4.24 shows the effect of increasing speed in the high speed class on P_N and P_H. P_N follows the same curve as D_N, as expected. P_H, on the other hand decreases sharply even when D_H is increasing, as H increases at a faster rate than D_H, as explained for the moderate speed class.

For the LR algorithm, the results of the moderate mean speed class are presented in Figures 4.19 to 4.21 whereas the results of the high mean speed class are presented in Figures 4.25 to 4.27. For both speed classes, LR behaves similarly as MR, except that in LR the number of new calls blocked and the number of handoff calls dropped differs from MR. LR has a lower D_N and a higher D_H than MR due to the fact that LR gives a higher chance for new calls to be served if free channels are available.

4.3.4 Effect of Mean Call Duration

The effect of changing the mean call duration on the probability of blocking and dropping calls is examined. The mean call duration is increased from 40 sec to 200 sec with a step size of 20 sec. The call duration has a direct effect on the number of handoffs generated. The results for the MR algorithm are presented in Figures 4.28 and 4.30. Figure 4.28 illustrate that as the call duration increase the number of handoff attempts increase. This is to be expected since mobile terminals with a

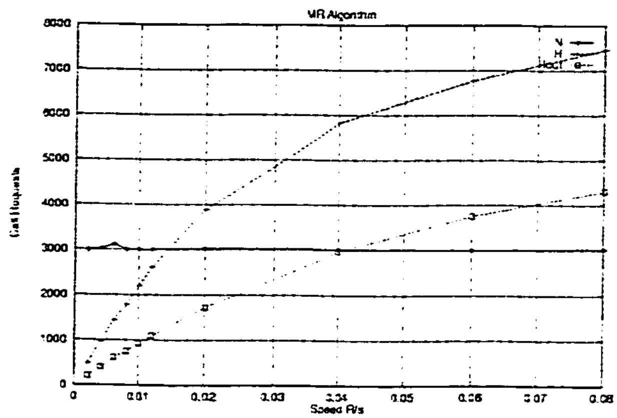

Figure 4.22: Effect of increasing the mean speed of the high speed class on N, H, and H_{out} for the MR algorithm.

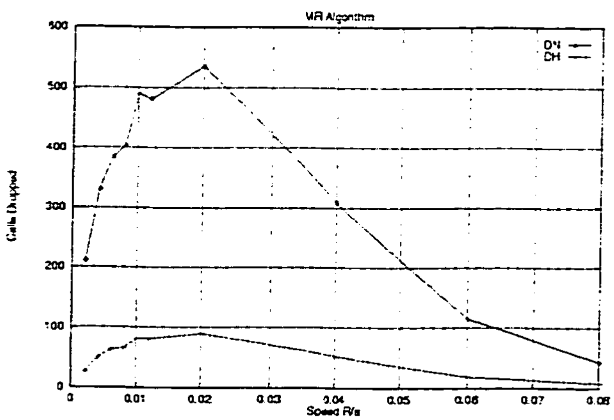

Figure 4.23: Effect of increasing the mean speed of the high speed class on D_N, and D_H for the MR algorithm.

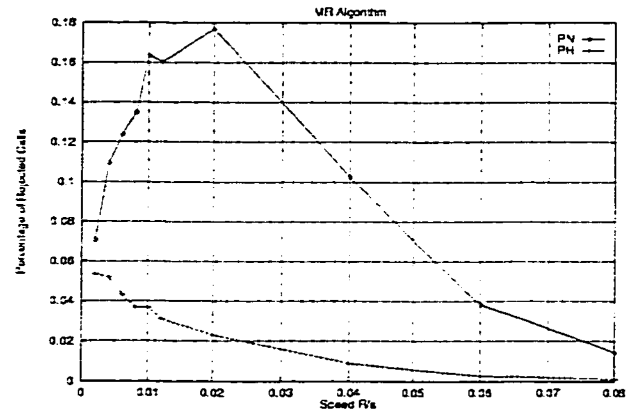

Figure 4.24: Effect of increasing the mean speed of the high speed class on P_N, and P_H for the MR algorithm.

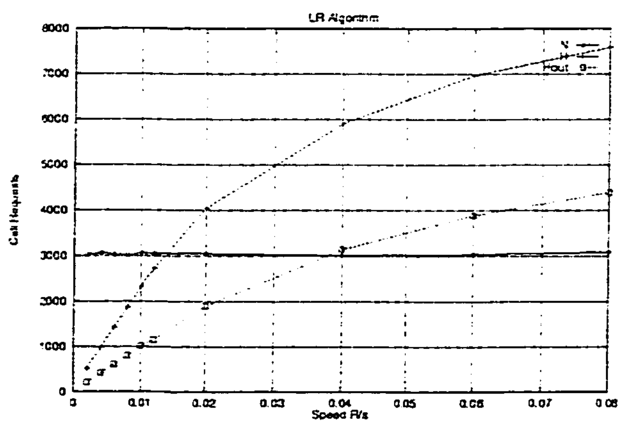

Figure 4.25: Effect of increasing the mean speed of the high speed class on N, H, and H_{out} for the LR algorithm.

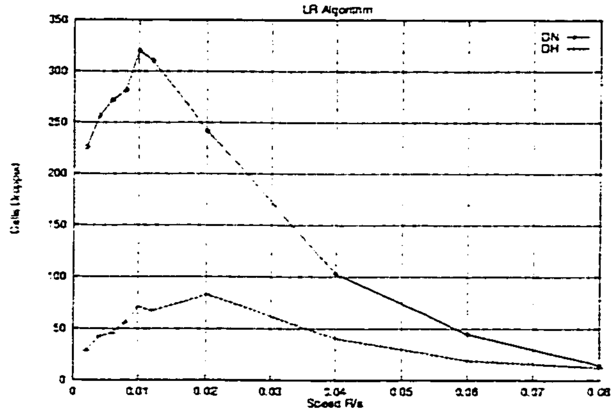

Figure 4.26: Effect of increasing the mean speed of the high speed class on D_N, and D_H for the LR algorithm.

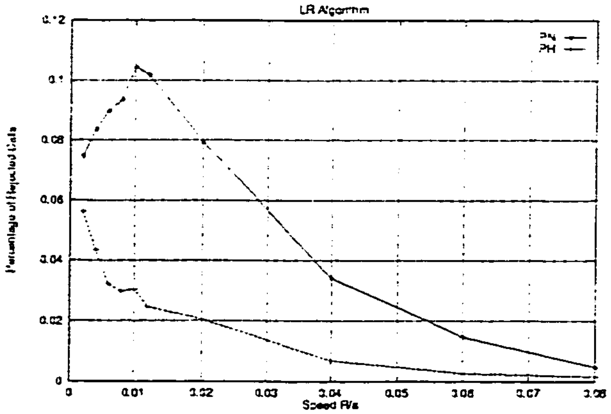

Figure 4.27: Effect of increasing the mean speed of the high speed class on P_N, and P_H for the LR algorithm.

longer call duration have a higher chance to cross cell boundaries. Since mobile terminals with a longer call duration cause the network resources to be locked by the communication session, new calls generated and calls handed-off to the network will be less likely to find free channels. Therefore, D_N and D_H increase with increasing call duration, as shown by Figure 4.29. In Figure 4.30 both the blocking and the dropping probabilities increase. The new call blocking probability increases since the new call arrival rate is constant and D_N is increasing. The handoff dropping probability increases because the rate of the increase in the handoff call attempts is higher than the rate of the increase in the handoff calls dropped.

The effects of increasing the call duration on LR are shown in Figures 4.31 to 4.33. In these experiments, both MR and LR follow the same behaviour, except that in LR the number of new calls blocked and the number of handoff calls dropped differs from MR. LR has a lower D_N and a higher D_H than MR due to the fact that LR gives a higher chance for new calls to be served if free channels are available.

The results of the moderate speed class for N, H, and H_{out} are similar to the results of the call duration for N, H, and H_{out} as shown in Figures 4.16 and 4.28. However, D_N and D_H for the moderate speed class do not follow the curve of D_N and D_H for the call duration. This can be explained as follows: for a mean speed 0.01 R/s, the mobile terminals need 200 sec to cross the cell diameter. Therefore, as the call duration increases, the probability that the call completes the communication session inside the cell is lower. Therefore, longer call duration causes the network resources to be locked by the communication session for a longer time period. Thus, as the call duration increases more calls are expected to be blocked as well as dropped. In Figure 4.16 for a call duration of 120 sec the mobile speed increases from 0.002 R/s (0.012 R/s). Therefore, the mobile terminal needs 500 sec (160 sec) to cross the cell boundary. Thus, the probability that a call is completed inside the cell is high and new calls generated and calls handed-off to the network will be more likely to find free channels.

4.3.5 Effect of Cell Radius

The effect of the cell radius on the performance of the MR and LR algorithms was examined, with the cell radius varying from 750 m to 2000 m. It can be guessed that

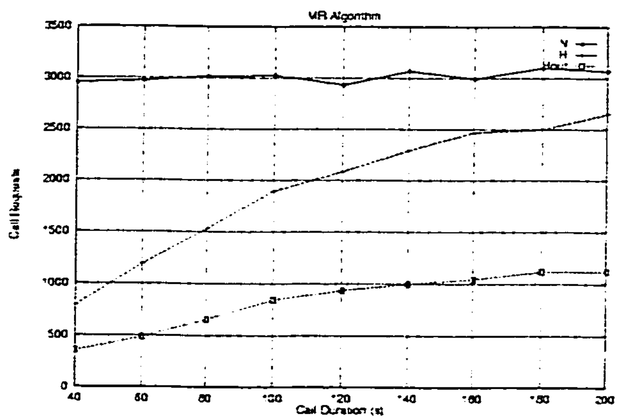

Figure 4.28: Effect of increasing the mean call duration on N, H, and H_{out} for the MR algorithm.

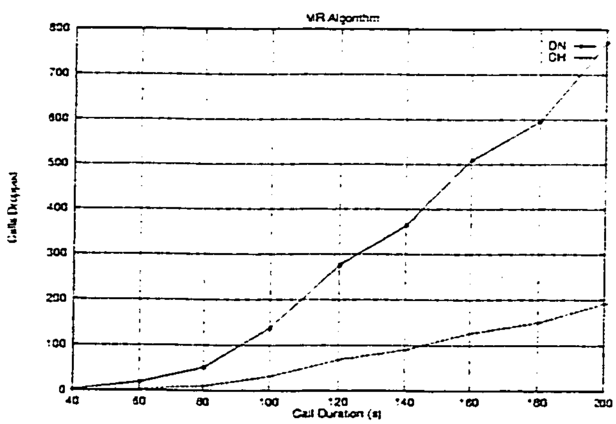

Figure 4.29: Effect of increasing the mean call duration on D_N, and D_H for the MR algorithm.

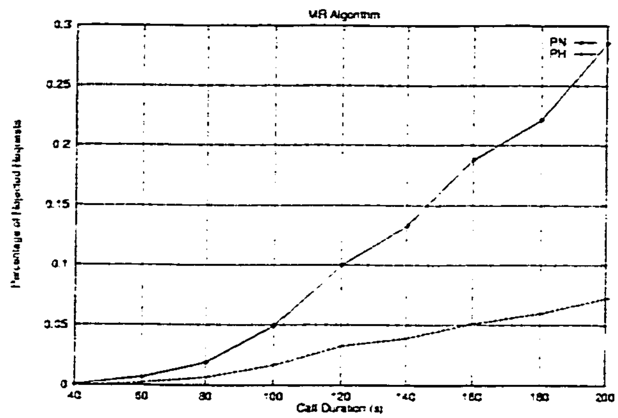

Figure 4.30: Effect of increasing the mean call duration on P_N, and P_H for the MR algorithm.

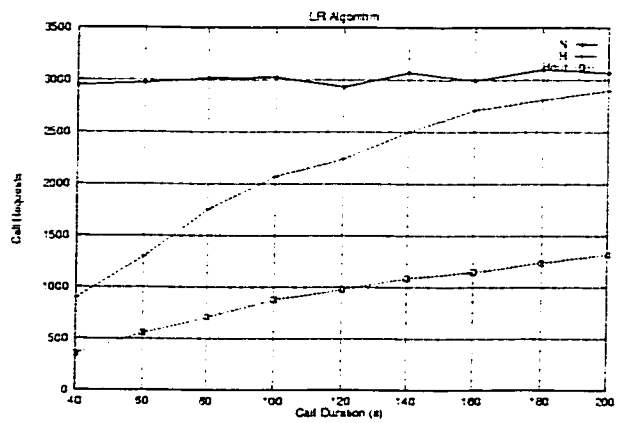

Figure 4.31: Effect of increasing the mean call duration on N, H, and H_{out} for the LR algorithm.

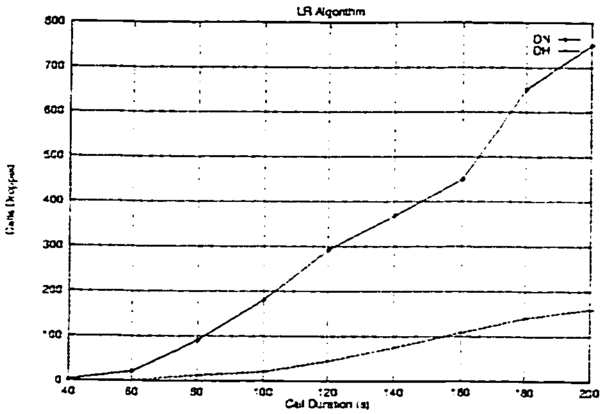

Figure 4.32: Effect of increasing the mean call duration on D_N, and D_H for the LR algorithm.

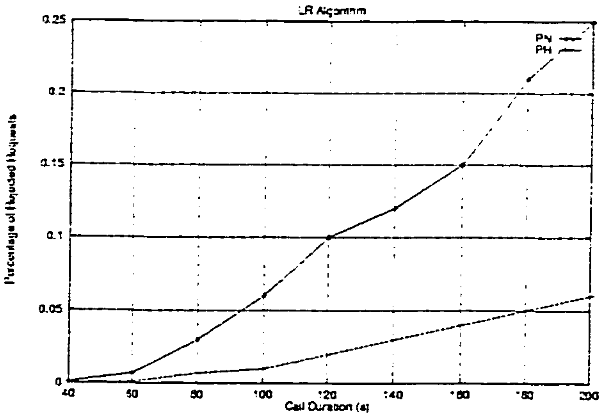

Figure 4.33: Effect of increasing the mean call duration on P_N, and P_H for the LR algorithm.

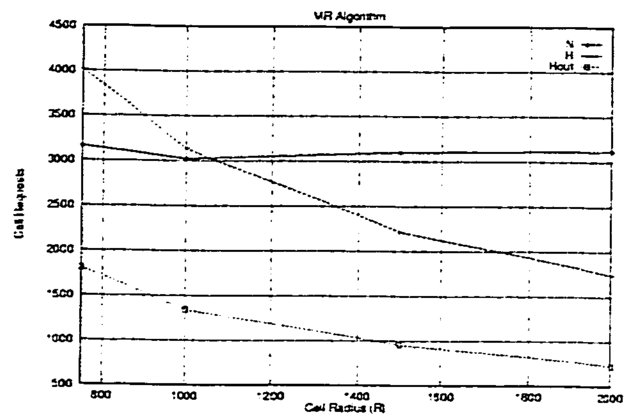

Figure 4.34: Effect of increasing the cell radius on N, H, and H_{out} for the MR algorithm.

the cell radius has a direct effect on the number of handoff attempts. As the cell radius increases, mobile terminals will be less likely to cross the cell boundary during the call session. The results for the MR algorithm are shown in Figures 4.34 to 4.36. In Figure 4.34, the number of new calls generated in each cell is constant and the number of handoff calls decreases as cell radius increases. Since more resources will be available, both D_H and D_N will decrease, this is shown in Figure 4.35. In Figure 4.36, P_N gradually decreases and P_H gradually increases. P_N decreases because the number of new calls generated is constant and the number of new calls dropped decreases. P_H increases since the number of handoff call attempts decrease faster than the decrease in the number of handoff calls dropped.

Figures 4.37 to 4.39 show the effect of increasing the cell radius on the behaviour of the LR algorithm. LR differs from MR in the number of new calls blocked and the number of handoff calls dropped. LR has a lower D_N and a higher D_H than MR due to the fact that LR gives a higher chance for new calls to be served if free channels are available.

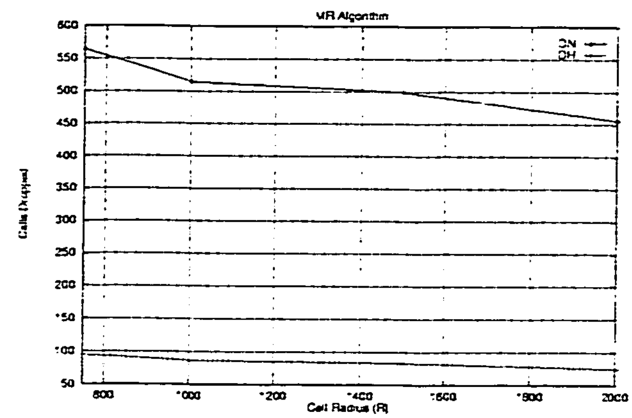

Figure 4.35: Effect of increasing the cell radius on D_N, and D_H for the MR algorithm.

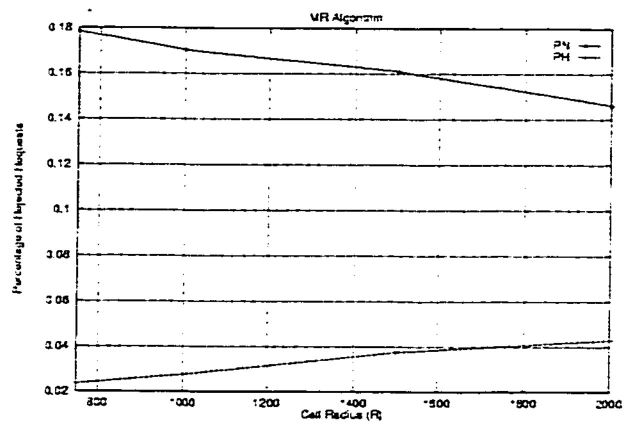

Figure 4.36: Effect of increasing the cell radius on P_N, and P_H for the MR algorithm.

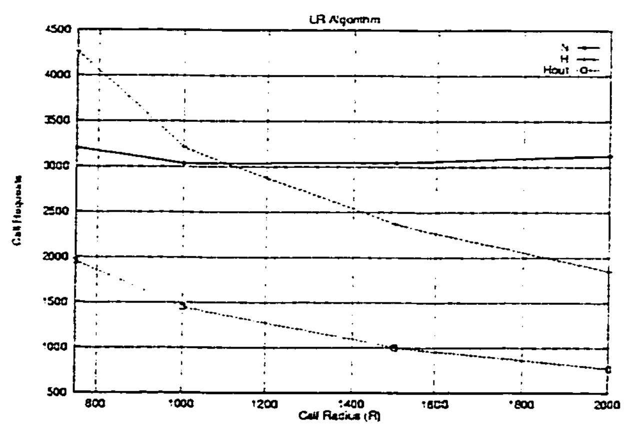

Figure 4.37: Effect of increasing the cell radius on N, H, and H_{out} for the LR algorithm.

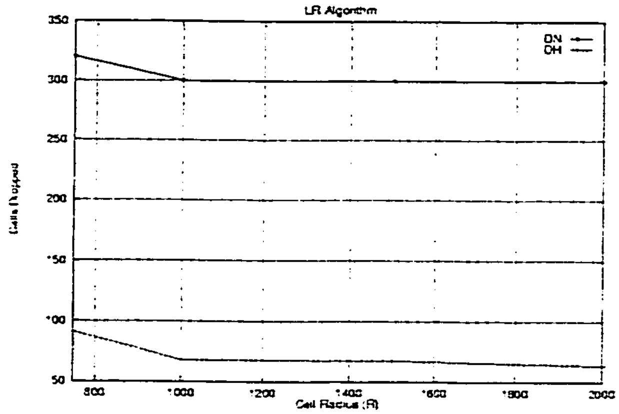

Figure 4.38: Effect of increasing the cell radius on D_N, and D_H for the LR algorithm.

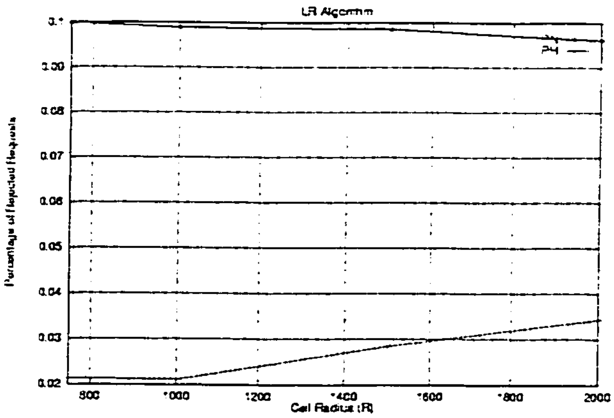

Figure 4.39: Effect of increasing the cell radius on P_N, and P_H for the LR algorithm.

4.4 Comparative Evaluation of LR, FTA, and ATA

In this section the performance of the LR algorithm is compared with the performance of the FTA and the ATA algorithms. In order to make a fair comparison, different call arrival rates are examined. The call arrival rates are divided into four classes, 7, 10, 15, and 20-channel class. For call arrival rates between 0.02- 0.05 calls/sec/cell, 7 channels are assigned to each cell with one guard channel reserved for handoff calls for the FTA and the ATA algorithms. When the call arrival rates are between 0.035-0.0655 calls/sec/cell, 10 channels are assigned to each cell with one guard channels reserved for handoff calls for the FTA and the ATA algorithms. For call arrival rates between 0.05 and 0.085 calls/sec/cell, each cell is assigned 15 channels with one guard channel reserved for handoff calls for the FTA and the ATA algorithms. Finally, if the call arrival rate is between 0.08 -0.1 calls/sec/cell, then 20 channels are assigned per cell with two guard channels reserved for handoff calls for the FTA and the ATA algorithms. An important parameter in the LR algorithm that should be carefully chosen is the best target dropping ratio for different new call arrival rates. A good value for the target dropping ratio would help to improve the system performance. From Section 4.2.1, we know that as X increases, P_N increases and P_H decreases. Therefore appropriate values of X should be assigned depending on the call arrival rate. Our experiments indicated that the best target dropping ratio for the 7-channel class was around $\frac{1}{6}$, for the 10-channel class was around $\frac{1}{7}$, for the 15-channel class was around $\frac{1}{9}$, and for the 20-channel class was around $\frac{1}{11}$. When comparing LR with other algorithms, we always use the above mentioned best value for a target dropping ratio.

In this section, we evaluate the performance of the three algorithms in terms of the GoS, P_{ns}, and channel non-utilization as performance measures. The new call blocking probability and the handoff dropping probability of the three algorithms are compared in Figure 4.40 to 4.47. As shown from Figures 4.40 to 4.43, LR has the lowest new call blocking probability over all the channel classes, while ATA has the lowest dropping probability as shown in Figures 4.44 to 4.47.

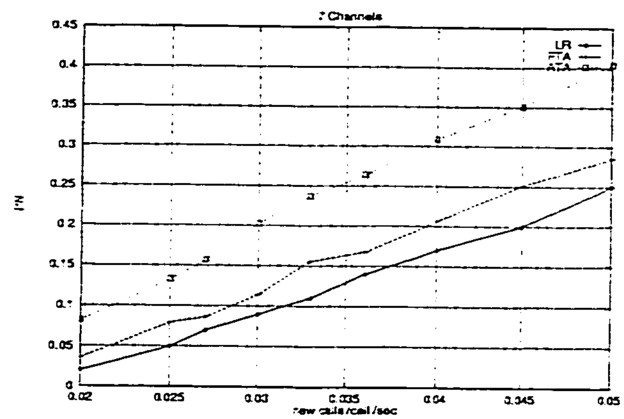

Figure 4.40: The probability of blocking new calls for LR, FTA, and ATA under the 7 channel class load.

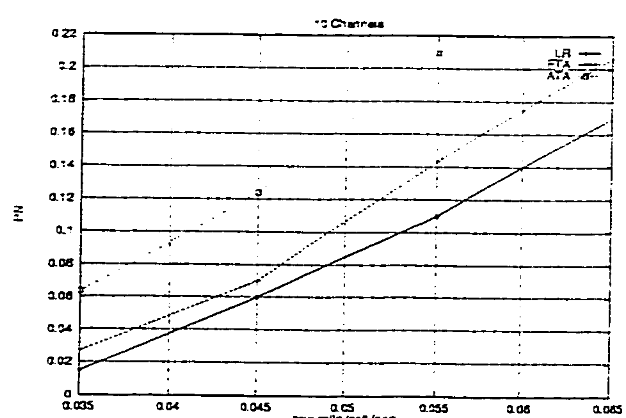

Figure 4.41: The probability of blocking new calls for LR, FTA, and ATA under the 10 channel class load.

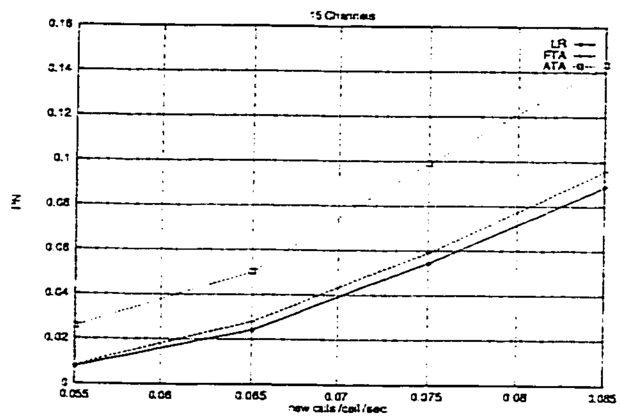

Figure 4.42: The probability of blocking new calls for LR, FTA, and ATA under the 15 channel class load.

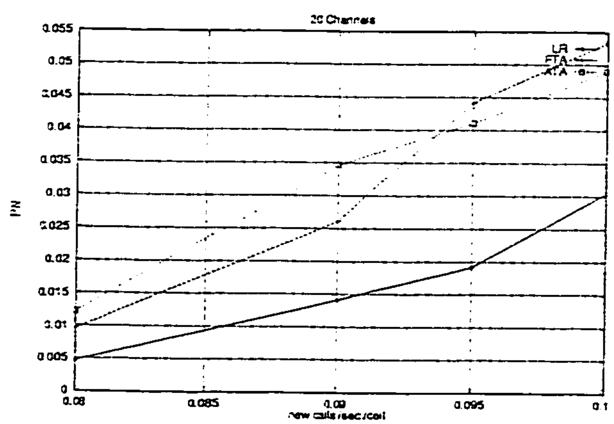

Figure 4.43: The probability of blocking new calls for LR, FTA, and ATA under the 20 channel class load.

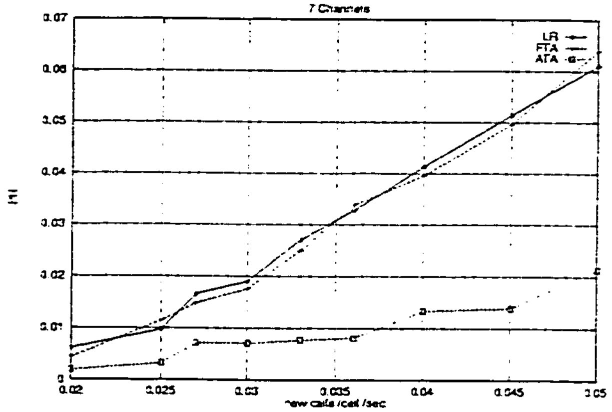

Figure 4.44: The probability of dropping handoff calls for LR, FTA, and ATA under the 7 channel class load.

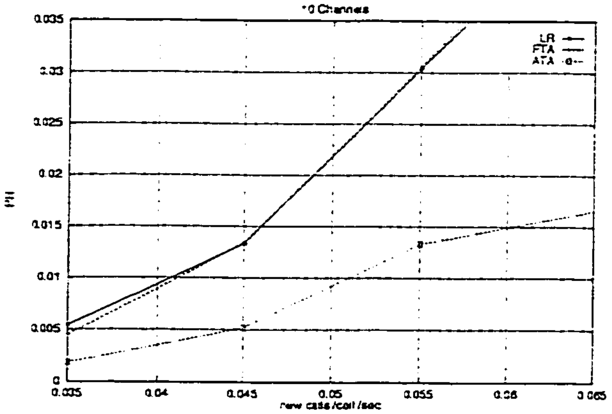

Figure 4.45: The probability of dropping handoff calls for LR, FTA, and ATA under the 10 channel class load.

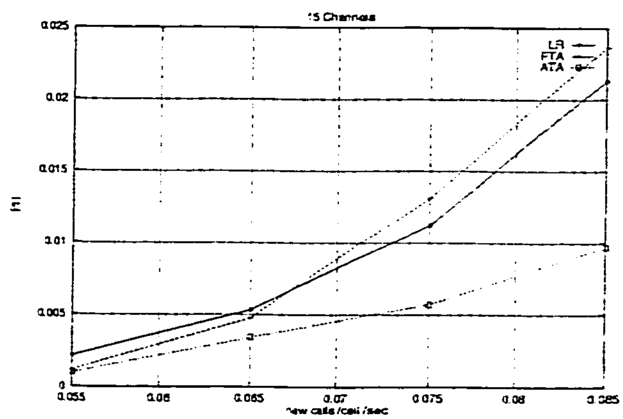

Figure 4.46: The probability of dropping handoff calls for LR, FTA, and ATA under the 15 channel class load.

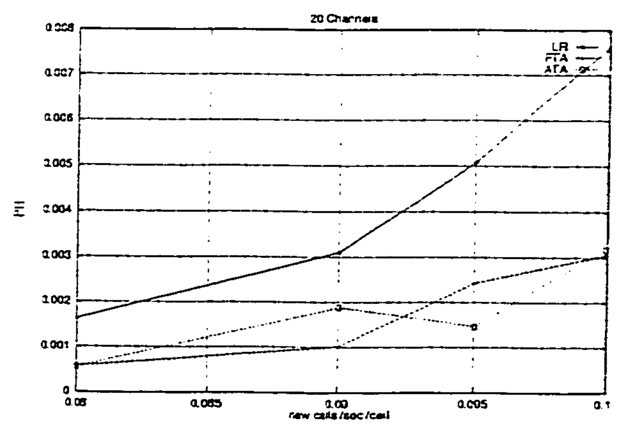

Figure 4.47: The probability of dropping handoff calls for LR, FTA, and ATA under the 20 channel class load.

4.4.1 Grade of Service (GoS)

Figures 4.48 to 4.51 compares the GoS of the three algorithms under different call arrival rates. LR and FTA have almost the same GoS for the different call arrival rates. However, ATA has the lowest GoS for the 7 and 10 channel classes. This is due to the fact that ATA reduces the handoff dropping probability at the cost of a high increase in the new call blocking probability. The new call blocking probability and the handoff dropping probability are shown in Figures 4.44 to 4.47 and Figures 4.40 to 4.43, respectively. For the 15 and 20-channel classes, the three algorithms have more or less the same GoS except when the new call arrival rate is greater than 0.075 call/sec with the 15-channel class. It can be concluded that giving handoff calls a very high priority does not always produce the minimum GoS.

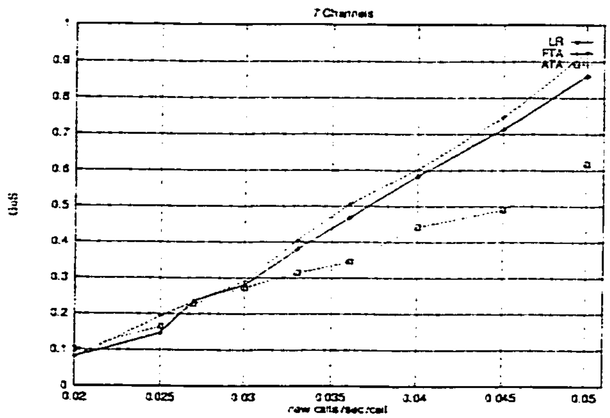

Figure 4.48: The GoS values for LR, FTA, and ATA under the 7 channel class load.

4.4.2 The Non-Completed Call Probability (P_{ns})

The non-completed call probability P_{ns} that was defined in Chapter 2 is another interesting performance measure. The P_{ns} values of the three algorithms are compared in Figures 4.52 to 4.55. Although ATA aims to achieve a low GoS, it has the highest non-completed call probability compared to FTA and LR. On the other hand, the LR algorithm has always the lowest P_{ns} since LR attempts to reduce the dropping probability as well as the blocking probability.

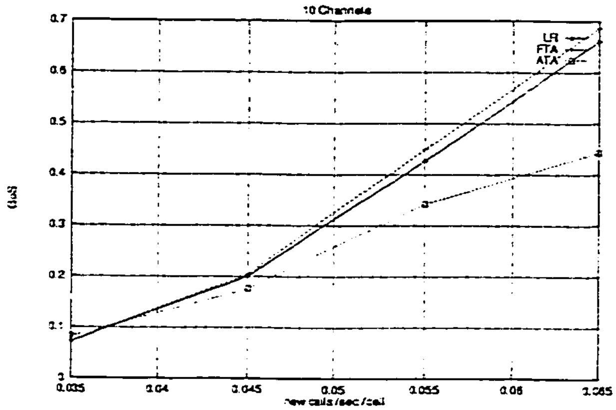

Figure 4.49: The GoS values for LR, FTA, and ATA under the 10 channel class load.

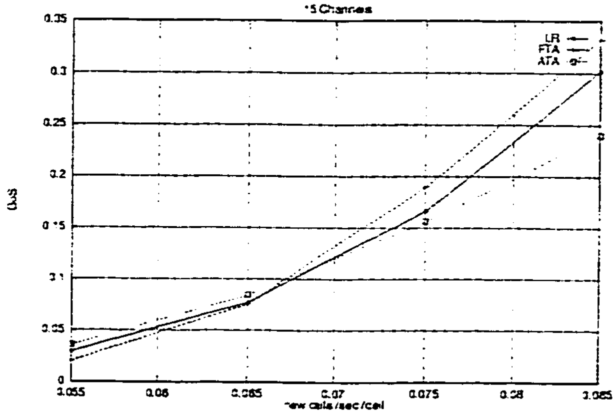

Figure 4.50: The GoS values for LR, FTA, and ATA under the 15 channel class load.

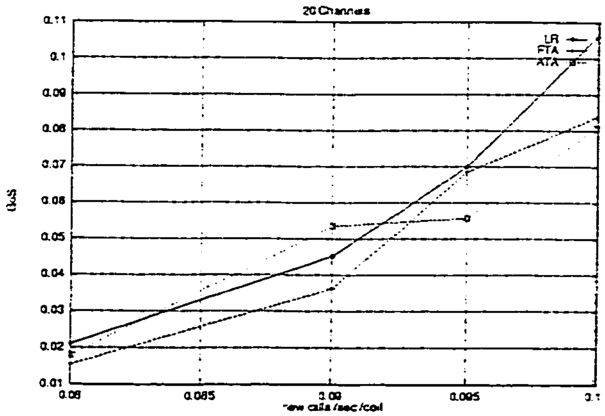

Figure 4.51: The GoS values for LR, FTA, and ATA under the 20 channel class load.

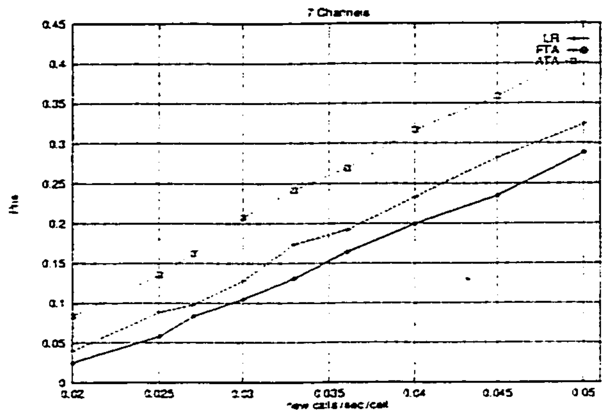

Figure 4.52: The P_{ns} values for LR, FTA, and ATA under the 7 channel class load.

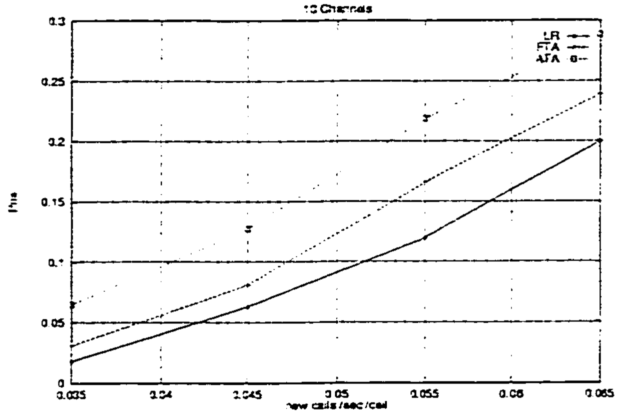

Figure 4.53: The P_{ns} values for LR, FTA, and ATA under the 10 channel class load.

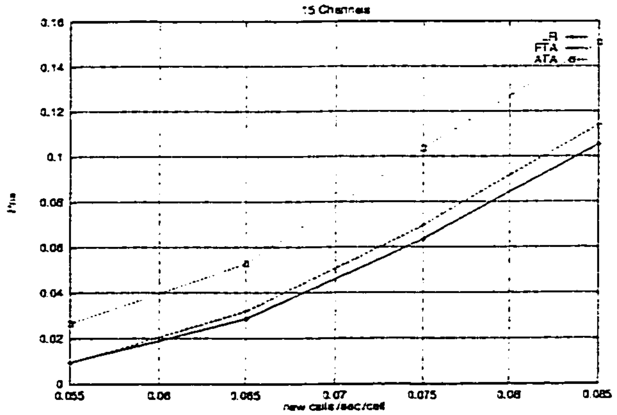

Figure 4.54: The P_{ns} values for LR, FTA, and ATA under the 15 channel class load.

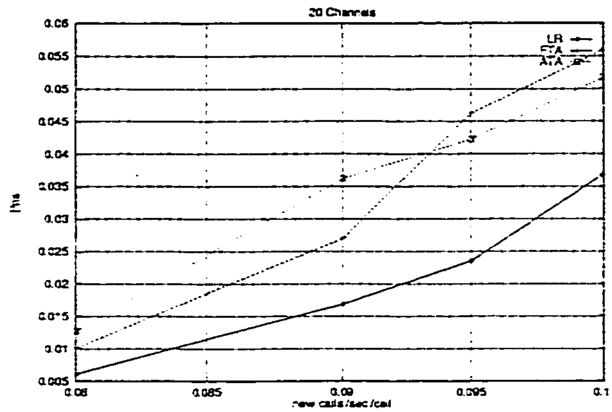

Figure 4.55: The P_{ns} values for LR, FTA, and ATA under the 20 channel class load.

4.4.3 The Channel Non-Utilization (γ)

The final performance measure that is evaluated is the channel non-utilization which is the average number of free channels available in the base station after each step. Figures 4.56 to 4.59 present the channel non-utilization for the three algorithms under different traffic loads. As expected, ATA has a lower channel non-utilization than FTA since ATA adaptively changes the number of guard channels based on the handoff requests. However, LR has the best channel non-utilization compared to FTA and ATA. This is due to the fact that LR uses the guard channel concept if and only if the dropping ratio was greater than the target ratio and the base station can accept all calls requesting service while FTA and ATA would use the concept of guard channels whenever it receives a new call request. In other words, LR uses the guard channel concept in fewer cases compared to FTA and ATA, which in turn achieves a lower channel non-utilization.

4.5 Concluding Remarks

In this chapter, the effect of changing cellular network parameters such as the target dropping ratio, new call arrival rate, cell radius, mobile terminal speed, and mobile call duration on the behaviour of the MR and LR algorithms was studied. Traffic load in cellular networks is heavily dependent on those parameters. The target dropping ratio

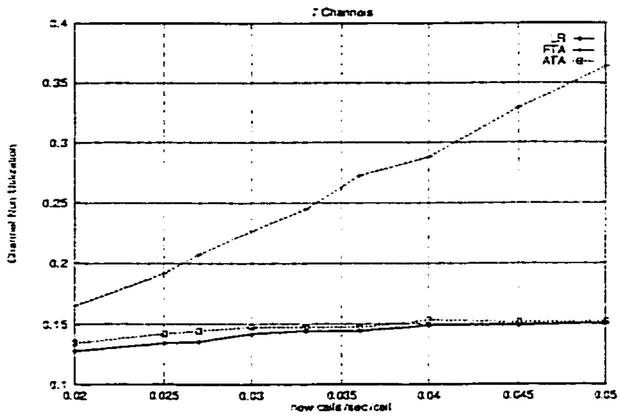

Figure 4.56: The channel non-utilization for LR, FTA, and ATA under the 7 channel class load.

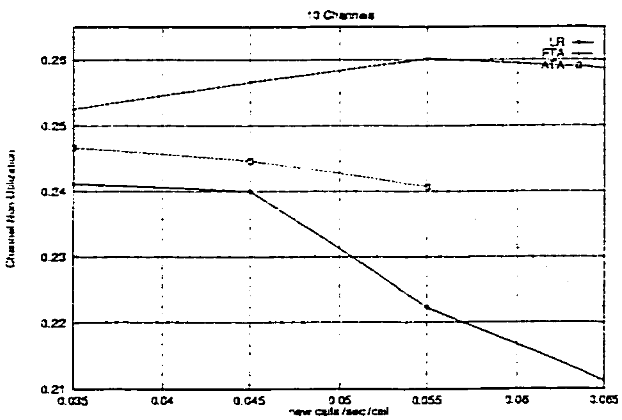

Figure 4.57: The channel non-utilization for LR, FTA, and ATA under the 10 channel class load.

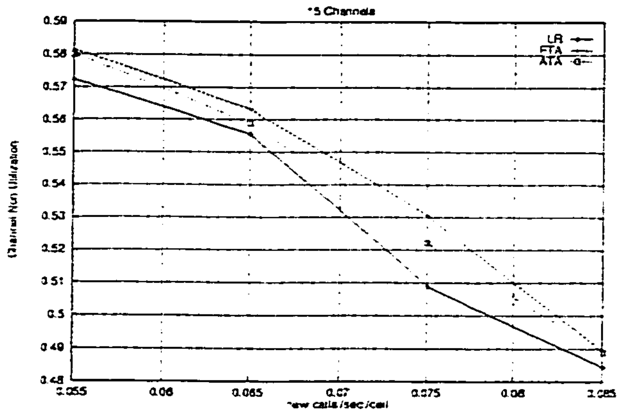

Figure 4.58: The channel non-utilization for LR, FTA, and ATA under the 15 channel class load.

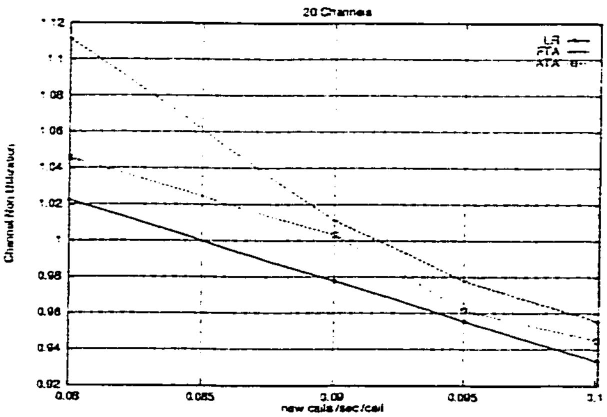

Figure 4.59: The channel non-utilization for LR, FTA, and ATA under the 20 channel class load.

is an important parameter that prioritizes handoff calls over new calls and directly affects the process of the acceptance of handoff and new call requests. Increasing the value of X would increase the priority of handoff calls over new calls. However, it also reduces the total number of new calls admitted to the network and hence the profit derived by the network providers. Therefore, using the best target dropping ratio for different new call arrival rates helps to improve the system performance. Our experiments indicated that for the LR algorithm the best target dropping ratio for the 7-channel class was around $\frac{1}{6}$, for the 10-channel class was around $\frac{1}{7}$, for the 15-channel class was around $\frac{1}{9}$, and for the 20-channel class was around $\frac{1}{11}$.

The new call arrival rate is the main source of load on the cellular network, if it increases, then the handoff call attempts would also be expected to increase. As a result, more calls are blocked as well as dropped. Thus, network providers should decide the level of priority to be given to handoff calls to achieve a good performance. The mobile terminal speed, the mobile call duration, and the cell radius determine the duration a channel will be used in a cell and the number of handoff calls during a call session. Particularly, those three parameters together affect the user mobility measured as in [38]: $\beta = \frac{R}{v_{mean} T_m}$. Note that β decreases as user mobility increases. Furthermore, the probability that a call in the current cell produces a handoff toward a neighboring cell P_h depends on β the mobility measure as in [38]:

$$P_h = \frac{1-e^{\beta}(1-\beta)}{2\beta} - \frac{\beta}{2}\int_{\beta}^{+\infty} \frac{e^{-x}}{x}\, dx.$$

Note that as β increases P_h decreases. Therefore, if the mobile terminal speed or the mobile call duration increases, the number of handoff call attempts would also be expected to increase since mobile terminals are more likely to cross the cell boundary during a communication session. However, if the cell radius increases, the total number of handoff call attempts would decrease since mobile terminal are less likely to cross the cell boundary during a communication session. An additional interesting effect that was observed was that if handoff call attempts increase very sharply, then so does the number of calls moving out of the network. This, in turn, causes channels to be freed, resulting in a decrease in blocking and dropping probabilities. Studying the effect of all these system parameters would help cellular network designers to predict the number of channels and the cell radius needed to support a certain number of users with a certain quality of service.

In this chapter, the performance of the LR algorithm was also compared with the performance of the FTA and the ATA algorithms. The LR algorithm is seen to provide lower new call blocking probability, and higher handoff dropping probability compared to FTA and ATA. The performance of the three algorithms was evaluated in terms of GoS, P_{ns}, and channels non-utilization. GoS is a cost function that prioritizes handoff calls over new calls, while P_{ns} is the probability that a call is not completed due to blocking of a new call or dropping of a handoff call. Our computational experiments showed that the LR algorithm, under different traffic loads, outperforms the FTA algorithms in terms of GoS, P_{ns} and channel non-utilization. Moreover, the LR algorithm has better performance than ATA algorithm in terms of P_{ns} and channel non-utilization under all the traffic loads but not for GoS under some traffic loads. This is because ATA achieves minimum GoS at the expense of high blocking probability for new calls, which the LR algorithm avoids.

Chapter 5

Conclusions and Future Work

In this thesis, we proposed two new call admission control algorithms, MR and a modified version LR. The MR algorithm is essentially based on defining a target dropping ratio that prevents dropping a handoff call unless a target number of new calls are blocked. Experiments showed that MR was dropping new calls unnecessarily. Therefore, some modifications were applied to MR to avoid this drawback. The modified version of MR , the LR algorithm, preserved the fundamental idea of the MR algorithm. LR aimed to improve the performance of the MR algorithm by giving new calls a higher chance to be served if there are free channels while additionally employing the idea of guard channels for handoff protection.

The performance of the MR and the LR algorithms was compared with different call admission control algorithms that were previously proposed in the literature. Although the performance of MR was superior to FCA, FCAHP, and FPA, it was worse than FTA and ATA. Therefore, it was interesting to compare quantitatively the modified version, the LR algorithm, with FTA and ATA. The three algorithms were compared in terms of the GoS, P_{ns}, and channel non-utilization under different traffic loads. Computational experiments showed that the LR algorithm outperforms the FTA algorithm in terms of GoS, P_{ns}, and channel non-utilization under all the traffic loads. It also has better performance than ATA in terms of P_{ns}, and channel non-utilization. However, ATA had a lower GoS than LR under some traffic loads. The ATA algorithm achieves the minimum GoS at the expense of high blocking probability for new calls. The results of the simulations clearly indicate the advantages the LR algorithm offers in terms of minimizing both the blocking and dropping probabilities and in terms of channel non-utilization. However, the LR algorithm is not optimal in the sense that there might be better algorithms resulting in lower blocking or dropping probability. Yet, LR is neither complex nor based on any impractical assumptions, and hence it is readily implementable. It is also shown to perform well under a variety of traffic loads.

The effects of several parameters on the system performance of the MR and LR algorithms are also studied. The target dropping ratio is an important parameter that affects the process of the acceptance of handoff and new call requests. Using the best dropping ratio for different new call arrival rates helps to improve the system performance. The behavior of the proposed algorithms in the case of call arrival rate fluctuations is also studied. Furthermore, we examined other parameters that affect the load of the cellular networks such as the cell radius, the call duration, and the mobile mean speed.

There is still potential work that can be done related to the design of the LR algorithm. First, we have assumed that the traffic load follows a uniform distribution. However, traffic in real cellular networks could be quite different. For future work, it would be worthwhile to investigate the effect of non-uniform traffic load distribution on the performance of LR. It also would be of interest if the algorithm can predict the behavior of the traffic and adaptively change the dropping ratio to achieve a minimum GoS. This can be implemented by developing a method that estimates the mobility of traffic based on the aggregated history of handoff calls observed in each base station. Using this estimate, the base station will adaptively change the target dropping ratio to achieve a good performance.

Bibliography

[1] I. F. Akyildiz and J. S. M. Ho, A Mobile User Location Update and Paging Mechanism under Delay Constraints, Proceedings of the Conference on Applications, Technologies, Architectures and Protocols for Computer Communications (ACM SIGCOMM '95), pp. 244-255, Cambridge, Massachusetts, 1995.

[2] I. F. Akyildiz, J. S. M. Ho and Y. Lin,Movement-Based Location Update and Selective Paging for PCS Networks, IEEE/ACM Transactions on Networking, Vol. 4, No. 4, pp. 629-638, August 1996.

[3] I. F. Akyidiz, J. McNair, J. Ho, H. Uzunalioglu and W. Wang, Mobility Management in Next Generation Wireless Systems, IEEE Proceedings Journal, Vol. 87, No. 8, pp. 1347-1385, August 1999.

[4] A. Acharya, J. Li, B. Rajagopalan and D. Raychaudhuri, Mobility Management in Wireless ATM Networks, IEEE Communications Magazine, pp. 100-109, November 1997.

[5] S. H. Bakry and N. Zawawi, An Initial Zone-splitting Design Method for Cellular Telephone Systems, International Journal of Networking Management, 9, pp. 291-297, 1999.

[6] C. Chang, C. Chang and K. Lo, Analysis of Hierarchical Cellular System with Reneging and Dropping for Waiting New and Handoff Calls, IEEE Transactions on Vehicular Technology, Vol. 48, No. 4, pp. 1080-1090, July 1999.

[7] S. Choi, and K. G. Shin, Predictive and Adaptive Bandwidth Reservation for Hand-Offs in QoS-Sensitive Cellular Networks, SIGCOMM, pp. 155-166, Vancouver, B.C., 1998.

[8] S. Choi, and K. G. Shin, Comparison of Connection Admission-Control Schemes in the Presence of Hand-Offs in Cellular Networks, MOBICOM, pp. 264-274, Dallas, Texas, 1998.

[9] C. Dhawan, Mobile Computing A System Integrator's Handbook, McGraw-Hill, 1997.

[10] S. Das, and S. K. Sen, A new Location Update Strategy for Cellular Networks and its Implementation using a Genetic Algorithm, MOBICOM, pp. 185-194, Budapest, Hungary, 1997.

[11] E. Ekici, and C. Ersoy, Optimal Two-Tire Cellular Network Design, IEEE IC-CCN, pp. 11-13, Boston, October 1997.

[12] B. Epstein, and M. Schwartz, Reservation Strategies for Multi Media Traffic in Wireless Environment, Proceedings of VTC '95, Chicago, Illinois, 1995.

[13] Y. Fang, I. Chlamtac, and Y. LinE. Ekici, and C. Ersoy, Modeling PCS Networks Under General Call Holding Time and Cell Residence Time Distributions, IEEE/ACM Transactions on Networking, Vol. 5, No. 6, pp. 893-906, December 1997.

[14] V.S. Frost, and B. Melamed, Traffic Modeling for Telecommunications Networks, IEEE Communications Magazine, pp. 70-81, March 1994.

[15] R. Guerin, Queuing-Blocking System with Two Arrival Streams and Guard Channels, IEEE Transactions on Communications, Vol. 36, No. 2, February 1988.

[16] A. Ganz, C. M. Krishna, D. Tang, and Z. J. Haas, On Optimal Design of Multitier Wireless Cellular Systems, IEEE Communications Magazine, pp. 88-93, February 1997.

[17] V.Garg, and J Wilkes, Wireless and Personal Communications Systems, New Jersey: Prentice Hall PTR, 1997.

[18] D. Hong, and S. S. Rappaport, Traffic Modeling and Performance Analysis for Cellular Mobile Radio Telephone Systems with Prioritized and Nonprioritized Handoff Procedures, IEEE Transactions on Vehicular Technology, Vol. VT-35, No. 3, pp. 77-92, August 1986.

[19] L. Hu, and S. S. Rappaport, Personal Communication Systems Using Multiple Hierarchical Cellular Overlays, IEEE Journal on Selected Areas in Communications, Vol. 13, No. 2, pp. 406-415, February 1995.

[20] Z. J. Haas, and Y. Lin, On Optimizing the Location Update Costs in the Presence of Database Failures, Wireless Networks, Vol. 4, pp. 419-426, 1998.

[21] A. Hac, and C. Mo, Dynamic Channel Assignement in Wireless Communication Network, International Journal of Network Management, pp. 44-66, September 1999.

[22] P. L. Hiew, and M. Zukerman, Teletraffic Issues Related to Channel Allocation in Digital Mobile Cellular Networks, IEEE INFOCOM98, pp. 43-50, 1998.

[23] R.H. Katz, Adaptation and Mobility in Wireless Information Systems, IEEE Personal Communications Magazine, Vol. 1, No. 1, pp. 6-17, First Quarter 1994.

[24] J. Janssen, K. Kilakos, and O. Marcotte, Fixed Preference Channel Assignment for Cellular Telephone Systems, IEEE Transcation on Vehicular Technology , Vol. 48, No. 2, pp. 533-541, March 1999.

[25] I. Katzela, and M. Naghshineh, Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey, IEEE Personal Communications, pp. 10-31, June 1996.

[26] X. Lagrange, Multitier Cell Design, IEEE Communications Magazine, pp. 60-64, August 1997.

[27] D.A. Levine, I. F. Akyildiz, and M. Naghshineh, A Resource Estimation and Call Admission Algorithm for Wireless Multimedia Networks Using the Shadow Cluster Concept, IEEE/ACM Transactions On Networking, Vol. 5, No. 1, pp. 1-12, February 1997.

[28] D. Lam, D. C. Cox, and J. Widom, Teletraffic Modeling for Personal Communications Services, IEEE Communications Magazine, pp. 79-87, February 1997.

[29] G.Y. Liu, and G. Q. Maguire Jr., Efficient Mobility Management Support for Wireless Data Services, Proceedings of VTC '95, Chicago, Illinois, 1995.

[30] X. Lagrange, and B. Jabbari, Fairness in Wireless Microcellular Networks, IEEE Transactions on Vehicular Technology, Vol. 47, No. 2, pp. 427-479, May 1998.

[31] J. Li, N. B. Shroff, and E. K. P. Chong, Channel Carrying: A Novel Handoff Scheme for Mobile Cellular Networks, IEEE Transactions on Networking, Vol. 7, No. 1, pp. 38-50, February 1999.

[32] J. Li, N. B. Shroff, and E. K. P. Chong, The Study of A Channel Sharing Scheme in Wireless Cellular Network including Handoffs, IEEE INFOCOM99,Vol. 9, pp. 1179-1186, 1999.

[33] B.L. Lim, and L. W. C. Wong, Hierarchical Optimization of Microcellular Call Handoff, IEEE Transactions on Vehicular Technology, Vol. 48, No. 2, pp. 459-466, March 1999.

[34] M. Nilsson, Third Generation Radio Access Standards, Ericsson Review On-Line, http://www.ericsson.com/review., No. 3, 1999.

[35] M. Oliver, and J. Borras, Performance Evaluation of Variable Reservation Polices for Hand-off Prioritization in Mobile Networks, IEEE INFOCOM99,Vol. 9, pp. 1187-1194, 1999.

[36] T. Ojanpera, and R. Prasad, An Overview of Third-Generation Wireless Personal Communications: A European Perspective, IEEE Personal Communications, pp. 59-65, 1998.

[37] S. Oh, and D. Tcha, Prioritized Channel Assignment in a Cellular Radio Network, IEEE Transactions on Communications, Vol. 40, No. 7, pp.1259-1269, July 1992.

[38] E. D. Re, R. Fantacci, and G.Giambene, Handover and Dynamic Channel Allocation Techniques in Mobile Cellular Networks, IEEE Transactions on Vehicular Technology,Vol. 44, No. 2,pp. 229-236, May 1995.

[39] C. Rose, and R. Yates, Location Uncertainty in Mobile Networks: A Theoretical Framework, IEEE Communications Magazine, pp. 94-101, February 1997.

[40] R. Steele, A Speculative Commentary on the Future: The Evolution of Personal Communications, IEEE Personal Communications Magazine, Vol. 1, No. 2,pp. 94-101, 1994.

[41] S. Saunders, Antennas and Propagation for Wireless Communication Systems , Chichester: John Wiley and Sons Ltd,1999.

[42] M. Sidi, and D. Starobinski, New Call Blocking versus Handoff Blocking in Cellular Networks, Proceedings of the Conference on Computer Communications (IEEE INFOCOM '96), 1996.

[43] S. Tekinay, and B. Jabbari, Handover and Channel Assignment in Mobile Cellular Networks, IEEE Communications Magazine, pp. 42-46, November 1991.

[44] S. Tekinay, and B. Jabbari, A Measurement-Based Prioritization Scheme for Handovers in Mobile Cellular Networks, IEEE Journal on Selected Areas in Communications, Vol. 10, No. 8, pp. 1343-1350, October 1992.

[45] N.D. Tripathi, J. H. Reed, and H. F. Vanlandingham, Handoff in Cellular Systems, IEEE Personal Communications, pp. 26-37, December 1998.

[46] V.V. Veeravalli, and O. E. Kelly, A Locally Optimal Handoff Algorithm for Cellular Communications, IEEE Transactions on Vehicular Technology, Vol. 46, No. 3, pp. 603-609, August 1997.

[47] W. Webb, Understanding Cellular Radio, Boston: Artech House, 1998.

[48] D. Wong, and T. J. Lim, Soft Handoffs in CDMA Mobile Systems, IEEE Personal Communications, pp. 6-17, December 1997.

[49] M. Zhang, and T. P. Yum, Comparisons of Channel-Assignment Strategies in Cellular Mobile Telephone Systems, IEEE Transactions on Vehicular Technology, Vol. 38, No. 4, pp. 211-215, November 1989.