MODELING AND ANALYSIS OF MULTI – TIER CELLULAR NETWORKS WITH DIFFERENT QUEUING SCHEMES

by

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ABSTRACT

The continuation of an active call is one of the most important quality measurements in cellular systems. Handoff process enables a cellular system to provide such a facility by transferring an active call from one cell to another. The principal parameters used to evaluate handoff techniques are: Forced termination probability, call blocking probability and call dropping probability. Different approaches are proposed and applied in order to achieve better handoff service. Mechanisms such as guard channels and queuing handoff calls decrease the forced termination probability while increasing the call blocking probability slightly. In order to increase system performance a second tier (macrocell layer) can be added on the top of existing tier (microcell layer) which utilizes the QoS parameters better.

In this thesis, one-tier and two-tier cellular networks are modeled using single dimensional and 2-D Markov chains. In each model, a FIFO queue or a number of guard channels is presented either in the microcell or the macrocell. The users are assigned to the appropriate layer due to their speeds, where the low speed users are assigned to the microcell and high speed users are assigned to the macrocell. Each network is then compared with the corresponding network to determine the effects of the queue and guard channels. Also, the effect of presenting the queue or guard channels in the microcell or macrocell is investigated.

Keywords: Handoff, Blocking Probability, Dropping Probability, FIFO Queue, Guard Channels, Two-Tier Cellular Networks, Markov Chains

ÇOK KATMANLI ŞEBEKELERİN ÇEŞİTLİ KUYRUKLAMA TEKNİKLERİNİ KULLANARAK MODELLENMESİ VE ANALİZİ

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ÖZ

Hücresel şebekelerde aktif konuşmanın devamlılığının sağlanması en önemli kalite ölçütlerinden biridir. Hücresel şebekelerde konuşmanın devamlılığı konuşmayı bir hücreden diğer bir hücreye aktarmak ile mümkündür. Bu aktarıma handoff işlemi adı verilir. Handoff işlemini değerlendirmek için kullanılan ana parametreler şunlardır: Zorunlu bitirme olasılığı, bloklama olasılığı ve düşürme olasılığı. Daha iyi bir handoff işlemi için değişik yaklaşımlar önerilmiş ve uygulanmıştır. Koruma kanalları ve handoff aramalarını kuyrukta bekletmek gibi mekanizmalar zorunlu bitirme olasılığını düşürürlerken arama bloklama olasılığını çok az arttırırlar. Sistem performansını arttırmak için birinci katmanın (microcell) üzerine ikinci bir katman (macrocell) eklenebilir.

Bu tez çalışmasında, bir ve iki katmanlı hücresel şebekeler Markov zincirleri kullanılarak modellenmiştir. Herbir modelde, microcell katmanında veya macrocell katmanında FIFO (ilk giren ilk çıkar) kuyrukları veya koruma kanalları kullanılmıştır. Kullanıcılar katmanlara hızlarına göre atanırlar; yavaş kullanıcılar microcell'e, hızlı kullanıcılar macrocell'e atanır. Herbir network FIFO kuyrukları ve koruma kanallarının etkilerini ortaya çıkarmak için aralarında karşılaştırılmıştır. Ayrıca, FIFO kuyruğunun veya koruma kanallarının microcell'de veya macrocell'de kullanımının etkileri de araştırılmıştır.

Anahtar Kelimeler: Handoff, Bloklama Olasılığı, Düşürme Olasılığı, FIFO Kuyruğu, Koruma Kanalları, İki Katmanlı Hücresel Şebekeler, Markov Zincirleri

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INTRODUCTION

Cellular systems have become very popular since their introduction in late 1970s. The ability to transfer voice over the wireless link is extended with various data applications such as Short Messaging Service (SMS), Multimedia Messaging Service (MMS), web browsing and e-mail applications, and even video conferencing. During the introduction of newer applications, the demand for higher data rates is growing. Each new generation of cellular network brought larger system capacity, increased voice quality and higher data rates to fulfill increased demand for cellular technologies.

The first generation (1G) cellular systems were introduced in late 1970s and in the first half of 1980s. The first generation cellular systems used analog signals and modulation techniques such as frequency modulation (FM). The cellular systems such as Advance Mobile Phone Service (AMPS) and The European Total Access Communication System (ETACS) are some of the example 1G systems (Rappaport, 2002).

The employment of digital signals and digital modulation introduced the second generation (2G) cellular systems which brought at least three times increased spectrum efficiency and improvements in security, performance and voice quality. The modulation techniques such as TDMA and CDMA are used in 2G networks. The well known examples of 2G systems are: Global System Mobile (GSM), Interim Standard 136 (IS - 136), Pacific Digital Cellular (PDC) and Interim Standard 95 Code Division Multiple Access (IS-95) (Rappaport, 2002), (Parry, 2002).

Second and half generation (2.5G) cellular networks are systems to provide a smooth transition to the third generation (3G) networks. 2.5G networks provide limited 3G services to their customers before the 3G networks are fully available. They increased the channel throughput three times in contrast to the second generation systems. Example systems are: High Speed Circuit Switched Data (HSCSD), General Packet Radio Service (GPRS), Enhanced Data Rates for GSM Evolution (EDGE) and Interim Standard – 95B (IS-95B) (Parry, 2002).

3G networks even provide higher speed data transmissions rates where data rates fall into three categories: 2 Mbps to stationary users, 384 Kbps to pedestrian users and 144 Kbps to vehicular users. Yet another great improvement is that 3G networks are expected to support international roaming without need to use a different cellular phone. The Universal Mobile Telecommunications System (UMTS) and CDMA2000 are two example of 3G cellular systems (Parry, 2002).

All the cellular systems discussed above deploy smaller cells in order to achieve high system capacity due to the limited spectrum. The frequency band is divided into smaller bands and those bands are reused in non-interfering cells. This technique is known as frequency reuse. Smaller cells cause an active mobile station (MS) to cross several cells during an ongoing conversation. This active call should be transferred from one cell to another one in order to achieve call continuation during boundary crossings. Handoff (or handover) is the process of transferring an active call from one cell to another.

The transfer of a current communication channel could be in terms of a time slot, frequency band, or a code word to a new base station (BS) (Pollioni, 1996), (Tripathi, 1998). If a new BS has some unoccupied channels, then it assigns one of them to the handed off call. However, if all of the channels are in use at the handoff time there are two possibilities: To drop the call or to delay it for a while. Some of the most important Quality of Service (QoS) metrics for evaluating handoff techniques and cellular networks performance are new call blocking probability, handoff call blocking probability, handoff call dropping probability and forced termination probability.

New call blocking and handoff call blocking probabilities are the probability of blocking such a request when that type of request is made to the target cell. Handoff dropping or handoff failure probability is the probability of blocking or dropping a handoff request.

Since the cell sizes become smaller in order to provide service to more customers, the number of cell boundary crossings increases as the mobile user speed increases. In order to solve the handoff problem for high speed users networks with two layers are proposed. In the first layer (microcell), the low speed users are served. A number of microcells are covered by a second layer (macrocell) where the high speed users are served and the cell size is larger than the microcell which reduces the number of crossings.

In a cellular network, the forced termination of an active call is less desirable by the mobile providers in contrast to blocking a new call request (Tekinay and Jabbari, 1991), (Tekinay and Jabbari, 1992), (Agrawal et al., 1996). In order to provide lower forced termination probability, prioritization schemes assign more channels to the handoff calls. The two well-known prioritization schemes are: Guard channels and queuing handoff calls (Tekinay and Jabbari, 1991), (Marichamy et al., 1999), (Tripathi et al., 1998) and (Tekinay and Jabbari, 1992).

The guard channel scheme reserves some fixed or adaptively changing number of channels for handoff calls only. The rest of the channels are used by new and handoff calls. So, the handoff calls are better served and forced termination probability is decreased. The costs of such a scheme are an increase in new call blocking probability.

Queuing handoff call prioritization scheme queues the handoff calls when all of the channels are occupied in a cell. When a channel is released, it is assigned to one of the handoff calls in the queue. A new call request is assigned a channel if the queue is empty and if there is at least one free channel in the cell.

In this thesis, an improvement of single and two-tier network models that were presented in (Salih, 2003) is proposed. A new performance parameter (handoff dropping probability) is also introduced and the number of channels used in the system is increased. Furthermore, two-tier networks employing guard channels are implemented as in (Hu and Rappaport, 1995) and compared to those having a FIFO queue in one of the tiers. All the models are analyzed by calculating steady state probabilities using single and multidimensional Markov chains. Using calculated steady states probabilities, new call blocking, handoff call blocking and handoff dropping probabilities are calculated for each network.

The results of two-tier networks having a FIFO queue in one of the tiers and two-tier networks having a number of guard channels in either the microcell or macrocell are compared with each other.

This thesis is divided into several chapters. Chapter 2 provides a general literature survey about cellular systems and handoff techniques. Then, in Chapter 3 the models for all single tier and two-tier networks employing a FIFO queue or guard channels are presented. Chapter 4 shows the results and comparisons of the proposed network models. At the end, conclusions and suggestions for future work is presented in Chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

In this Chapter a literature survey is conducted related to cellular telephone systems and general handoff issues. The chapter is divided into several sections. In Sections 2.2 and 2.3, cellular telephone systems and multiple access techniques are investigated. The survey then continues with performance metrics of cellular networks in Section 2.4. The handoff initiation, handoff decision and handoff types are presented in Sections 2.5, 2.6 and 2.7, respectively. Finally, prioritization schemes are introduced in Section 2.8.

2.2 CELLULAR TELEPHONE SYSTEMS

Cellular systems provide wireless access to the Public Switch Telephone System and other subscribers in the cellular system. To achieve the demand of high quality service and large amount of subscribers, the systems limits the range of their base stations so the base stations in non-interfering distance can use same frequency band leading increased system capacity. This technique is known as frequency reuse and examples are 3, 5 and 7 cell reuse patterns. A basic cellular system consists of mobile stations (MS), base stations (BS) and mobile switching centers (MSC). The mobile station (mobile device or user), has a transceiver antenna and exchange voice signals with a base station which can have more than one transmitter and receiver antenna. Most of the time, a base station is mounted on high places such as the top of a building or a traffic light. The MSCs are responsible for the administration of the entire cellular system and switching calls to the PSTN.

2.2.1 First Generation (1G) Cellular Systems

Developed by AT&T Bell Labs in late 1970s, Advanced Mobile Phone Service (AMPS) was deployed in 1983, Chicago as the first US cellular system. Being a member of 1G cellular system, AMPS used large cells with a seven-cell reuse pattern to increase the system capacity. It is deployed at 800 MHz band with 30 kHz channels those use frequency modulation (FM) for voice modulation, frequency division multiple access (FDMA) and frequency division duplex (FDD) (Rappaport, 2002).

Another AMPS like system of 1G family is The European Total Access Communication System (ETACS), introduced in 1985. It is almost identical to AMPS except the bandwidth of channels which uses 25 kHz ones. Decreased channel bandwidth increases the available channels of AMPS from 832 to 1000 (Rappaport, 2002).

2.2.2 Second Generation (2G) Cellular Systems

The second generation (2G) cellular systems conform to the second generation cellular standards. The well known examples of 2G systems are: Global System Mobile (GSM), Interim Standard 136, Pacific Digital Cellular (PDC) and Interim Standard 95 Code Division Multiple Access (IS-95). The difference between 1G and 2G relies on signals and techniques based on the signals. 1G uses the analog signals whereas 2G systems employ digital signals. All the 2G systems offer at least a three-times increase in spectrum efficiency as compared to 1G systems and improvements in security, performance and voice quality. The efficiency is achieved by using digital modulation formats such as BPSK with Quadrature Spreading, GMSK and DQPSK and multiple access technologies Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). All the discussed systems above except IS-95 use TDMA (Rappaport, 2002), (Parry, 2002).

The most popular cellular system worldwide is the Global System Mobile (GSM) and is the first digital wireless technology introduced in 1991. In 2001, it had a 60% market share and over 350 million subscribers worldwide. The frequency bands used for uplink are 890-915 MHz in Europe and 1850-1910 MHz in U.S. The frequency bands used for downlink are 935-960 MHz in Europe and 1930-1990 MHz in U.S. A combination of FDMA and TDMA is used in GSM where a 200 kHz channel is divided into time slots. The digital modulation scheme used in GSM is Gaussian Minimum Shift Keying (GMSK) and is designed specifically for GSM (Parry, 2002), (Rappaport, 2002).

GSM offers two types of services classified as teleservices and data services. Teleservices include standard mobile telephony and mobile originated or base-originated traffic. Data services include computer to computer communication and packet switched traffic (Rappaport, 2002).

The GSM system architecture is consisted of three subsystems that interact between themselves. The subsystems are Base Station Subsystem (BSS), Network and Switching Subsystem (NSS) and the Operation Support Subsystem (OSS).

The BSS also known as Radio Subsystem provides and manages the radio transmission paths between the mobile stations and the Mobile Switching Center (MSC). Each BSS consists of many Base Station Controllers (BSC) and base transceiver stations (BTS). BTS transmits and receives radio signals and is controlled by BSC. The air interface connecting a BTS to a BSC is called the Abis interface. This interface carries traffic and maintenance data. BSC controls the BTSs and handles channel setup, handoff and frequency hopping. The air interface between mobile station (MS) and BTS is GSM Radio Air Interface. The MS is considered to be part of BSS and consists of mobile handset (device) and Subscriber Identity Module (SIM) card. The SIM card is responsible for reception, initiation and termination of calls (Rappaport, 2002).

The NSS manages the switching functions of the system and allows the MSCs to communicate with other network such as PSTN and ISDN. MSC is the central unit in the NSS and controls the traffic among all of the BSCs. MSCs are connected to the BSCs via physically links using A interface. The Gateway Mobile Switching Center (GMSC) acts as an interface between the mobile network and other fixed networks. Routing calls to fixed network is done by GMSC (Rappaport, 2002).

The OSS supports the operation and maintenance of GSM and allows monitoring, diagnosing and troubleshooting of the GSM system. The three main functions of the OSS are: to maintain all telecommunications hardware and network operations, to manage all charging and billing procedures, and to manage all mobile equipment in the system (Rappaport, 2002).

Also known as United States Digital Cellular or North American Digital Cellular, Interim Standard 136 (IS-136) uses TDMA to achieve 3 full duplex or 6 half duplex voice channels per carrier by dividing each carrier to 6 time slots. IS-136 is designed to use same frequencies, frequency reuse pattern, and base stations of AMPS.

Pacific Digital Cellular (PDC) is a TDMA based cellular system which is introduced in 1991 in Japan. It is very similar to American IS-136 with some exceptions. As opposed to IS-136 it uses 1500 MHz frequency band and channels with 25 kHz bandwidth each (Personal Digital Cellular (PDC) – the 2G system used in Japan).

Interim Standard 95 (IS-95) is introduced in 1993 and is compatible with previous AMPS deployment as IS-136. The main difference between IS-95 and other 2G systems is that it exploits the use of CDMA multiple access technique. All the users in a CDMA cell and neighboring cells can use same radio channel to transmit their signals. It is achieved by the use of orthogonal codes known as Walsh codes which enables 64 users to transmit signals simultaneously on same radio channel. Each channel's bandwidth is 1.25 MHz (Rappaport, 2002), (Parry, 2002).

2.2.3 Two And Half Generation (2.5G) Cellular Systems

2.5G cellular networks provide a transition from 2G networks to the 3G ones. The cost of replacing 2G equipment with new 3G equipments is very high. 2.5G networks provide limited 3G services to their customers before the 3G networks are fully available (Parry, 2002).

High Speed Circuit Switched Data (HSCSD) is a circuit switched technique based on GSM. The mobile user use consecutive time slots instead of using dedicated time slot in the GSM TDMA. Using multiple time slots enables user to achieve higher data rates. HSCSD also doesn't use the error control coding algorithms and increase the channel capacity from 9.600 bps up to 14.400 bps. Using 4 consecutive time slots, HSCSD can provide a raw transmission rate up to 57.600 kbps (Rappaport, 2002).

General Packet Radio Service (GPRS) is a packet-based data network built on the top of GSM. It achieves higher data rates by dynamically assigning time slots on GSM radio channel. GPRS can support much more users from HSCSD because of its packet based nature. To connect to a data network, a serving GPRS support node and a GPRS backbone network with a gateway GPRS support node is added to the GSM architecture to provide GPRS support. Data transmission rates up to 171.2 kbps are possible (Parry, 2002).

Enhanced Data Rates for GSM Evolution (EDGE) supports both voice and data transmission. It provides significant date rate improvements by using eight level phase shift keying (8PSK) modulation instead of GSM's two level GMSK modulation. EDGE provides a channel throughput of 69.2 kbps in contrast to the GSM's 22.8 kbps. Using multiple time slots, a throughput total of 474 kbps can be achieved in EDGE. New hardware and software upgrades are required at existing base stations of GSM to support EDGE (Parry, 2002), (Rappaport, 2002).

IS-95B is the only CDMA upgrade in path of 3G evolution. It provides high speed packet and circuit switched data access on a common CDMA radio channel by assigning multiple code words to a user. A throughput of 115.2 kbps is reached by assigning user 8 code words (Rappaport, 2002).

2.2.4 Third Generation (3G) Cellular Systems

Third generation (3G) networks standards are proposed by International Telecommunications Union (ITU) which defines advanced services especially data services. 3G provides high speed data transmissions where data rates fall into three categories: 2 Mbps to stationary users, 384 Kbps to pedestrian users and 144 Kbps to vehicular users. 3G also provides symmetrical and asymmetrical data transmission support and improved voice quality. Yet another great improvement is that 3G networks are expected to support international roaming without need to use a different cellular phone (Parry, 2002).

The Universal Mobile Telecommunications System (UMTS), also referred as WCDMA, has evolved since late 1996 and submitted to ITU in 1998. UMTS assures backward compatibility with the 2G GSM, IS-136 and PDC and 2.5G TDMA technologies. The UMTS air interface standard is designed for packet based wireless service and packet data rates of 2.048 Mbps per user is provided. It requires a minimum spectrum allocation of 5MHz bandwidth and provides at least a six time increase in spectral efficiency over GSM (Pappaport, 2002).

cdma2000 is an upgrade to its predecessors 2G cdmaOne and 2.5G IS-95B and is backward compatible with those systems. Peak data rates of 153 kbps are possible with low-end phones and data rates of 307 kbps are possible with high-end phones and devices (Parry, 2002).

2.3 MULTIPLE ACCESS TECHNIQUES

Radio systems use multiple access schemes in order to increase system capacity by sharing the wireless medium in different ways. The three major multiple access techniques are: Frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA). The future multiple access techniques are packet radio (PR) and space division multiple access (SDMA).

In FDMA systems the medium is divided to some number of narrow channels and each user is assigned a pair of channels in order to achieve full duplex communication. Each FDMA channel is used by only one user and it limits the wireless system utilization because of wasting the channel during the idle periods. Some cellular systems using FDMA are: AMPS, Cordless Telephone (CT2) and Digital European Cordless Telephone (DECT).

Instead of dividing wireless medium into narrow frequency channels, it is divided into time slots in TDMA. Each user can use that time slot either to transmit or receive wireless signals. In TDMA systems the data and modulation are both digital while FDMA systems use analog ones resulting in increased system complexity. The higher system complexity is due to digital modulation and synchronization of time slots at receiver and transmitter. Global System for Mobile (GSM), PDC, and IS-136 are some systems that use TDMA.

As opposed to FDMA and TDMA systems, the CDMA systems do not divide the spectrum into smaller parts. All the users use the same spectrum to send and receive wireless signals. The multiple access is achieved by coding each users signal by an orthogonal codeword. When the sender and receiver have that common codeword, they can encode the original wireless signal and perform communication. The number of orthogonal codewords is limited based on bandwidth of spectrum, but is much higher than those of FDMA and TDMA. IS-95, cdma2000 and W-CDMA systems are example systems that employ use of CDMA (Rappaport, 2002).

2.4 PERFORMANCE METRICS OF CELLULAR NETWORKS

Some of the most important Quality of Service (QoS) metrics for evaluating handoff techniques and cellular networks performance are new call blocking probability, handoff call blocking probability, handoff call dropping probability and forced termination probability. New call blocking and handoff call blocking probabilities are the probability of blocking such a request when that type of request is made to the target cell. Handoff dropping or handoff failure probability is the probability of blocking or dropping a handoff request. Two possibilities can occur in handoff dropping: first all the channels and queues are occupied so the call is blocked or second a handoff call in the queue can not acquire a channel in its queue time so the call is dropped. The forced termination probability is the probability of dropping an active call due to handoff failure before the call is completed (Pollioni, 1996), (Tekinay and Jabbari, 1992) and (Iera et al., 2002). The aim of a handoff technique is to decrease forced termination probability while not increasing call blocking probability significantly.

2.5 HANDOFF INITIATION

Handoff initiation is the process of deciding when to request a handoff. Handoff decision is based on the received signal strengths (RSS) from the current BS and neighboring BSs. In Fig. 2.1, we examine the RSSs of the current BS (BS1) and one neighboring BS (BS2). The RSS gets weaker as the MS moves away from BS1 and gets stronger as it gets closer to BS2 as a result of signal propagation characteristics. The received signal is averaged over time using an averaging window to remove momentary fadings due to geographical and environmental factors (Tekinay and Jabbari, 1991) and (Pollioni, 1996). Below, we will examine the four main handoff initiation techniques mentioned in (Pollioni, 1996) and (Marichamy et al., 1999): relative signal strength, relative signal strength with threshold, relative signal strength with hysteresis, and relative signal strength with hysteresis and threshold.

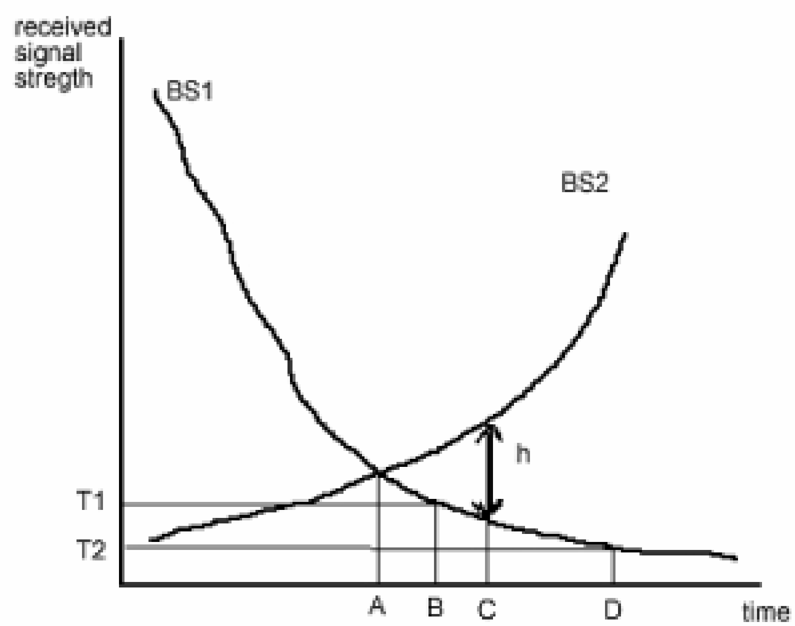

Figure 2.1 Movement of a MS in the handoff zone.

In relative signal strength, the RSSs are measured over time and the BS with strongest signal is chosen to handoff. In Fig. 2.1, BS2's RSS exceeds RSS of BS1 at point A and handoff is requested. Due to signal fluctuations, several handoffs may be requested while BS1's RSS is still sufficient to serve the MS. These unnecessary handoffs are known as the *ping-pong* effect.

As the number of handoffs increase, forced termination probability and network load also increases. Therefore, handoff techniques should avoid unnecessary handoffs.

Relative signal strength with threshold introduces a threshold value (T1 in Fig. 2.1) to overcome the ping-pong effect. The handoff is initiated if BS1's RSS is lower than the threshold value and BS2's RSS is stronger than BS1's. The handoff request is issued at point B in Fig. 2.1.

Relative signal strength with hysteresis technique uses a hysteresis value (h in Fig. 2.1) to initiate handoff. Handoff is requested when the BS2's RSS exceeds the BS1's RSS by the hysteresis value h (point C in Fig. 2.1).

The last technique combines both the threshold and hysteresis values concepts to come up with a technique with minimum number of handoffs. The handoff is requested when the BS1's RSS is below the threshold (T1 in Fig. 2.1) and BS2's RSS is stronger than BS1's by the hysteresis value h (point C in Fig. 2.1). If we would choose a lower threshold than T1 (but higher than T2) than the handoff initiation would be somewhere at the right of point C.

All the techniques discussed above initiate handoff before point D, which is the "receiver threshold". The receiver threshold is the minimum acceptable RSS for call continuation (T2 in Fig. 2.1) due to (Tekinay and Jabbari, 1991) and (Gudmundson, 1991). If the RSS drops below the receiver threshold, the ongoing call is than dropped. The time interval between the handoff request and receiver threshold enable cellular systems to delay the handoff request until the receiver threshold time is reached when the neighboring cell does not have any empty channels. This technique is known as queuing handoff calls.

In (Kim et al., 1996), a handoff algorithm using multi-level thresholds is proposed which assigns different threshold values to the users according to their speed. Since low speed users spend more time in handoff zone they are assigned a higher threshold to distribute high and low speed users evenly. High speed users are assigned lower thresholds. The performance results obtained by (Kim et al., 1996) shows that an 8-level threshold algorithm operates better than a single threshold algorithm in terms of forced termination and call blocking probabilities.

In (Moghaddam et al., 2000) and (Vakili and Moghaddam, 2000), an improved threshold-based method is introduced and compared with the basic initiation techniques such as maximum power handoff (MPH or RSS), RSS with hysteresis, RSS with threshold, and combinations of hysteresis and threshold based methods in a ten-cell structure.

2.6 HANDOFF DECISION

In the previous section, we discussed the time in which a handoff is requested. In this section, we will examine the handoff decision protocols used in various cellular systems.

Network Controlled Handoff (NCHO) is used in first generation cellular systems such as Advanced Mobile Phone System (AMPS) where the mobile telephone switching office (MTSO) is responsible for the overall handoff decision (Tanenbaum, 2003). In NCHO, the network handles all the necessary RSS measurements and handoff decision. The handoff execution time is on the order of many seconds because of the high network load (Noerpel and Lin, 1997).

In NCHO, the load of the network is high since the network handles all of the processes itself. In order to reduce the load of the network, the MS is responsible for making RSS measurements and sending them periodically to BS in Mobile Assisted Handoff (MAHO). Based on the received measurements, the BS or the mobile switching center (MSC) decides when to handoff (Marichamy et al., 1999) and (Tripathi et al., 1998). MAHO is used in the Global System for Mobile Communications (GSM). The handoff execution time is about 1 sec (Tripathi et al., 1998), (Noerpel and Lin, 1997).

Mobile Controlled Handoff (MCHO) extends the role of the MS by giving overall control to it. Both, MS and BS, make the necessary measurements, and the BS sends them to the MS (Marichamy et al., 1999). Then, the MS decides when to handoff based on the information gained from the BS and itself. Digital European Cordless Telephone (DECT) is a sample cellular system using MCHO with 100-500 ms handoff execution time (Tripathi et al., 1998), (Noerpel and Lin, 1997).

2.7 HANDOFF TYPES

In this section we will investigate the different types of handoffs. First, we will concentrate on channel usage. Then, we will investigate handoff in microcells and multilayered systems. Finally, we will explain handoff in homogeneous and heterogeneous systems.

2.7.1 Hard vs. Soft Handoff

The hard handoff term is used when the communication channel is released first and the new channel is acquired later from the neighboring cell. Thus, there is a service interruption when the handoff occurs reducing the quality of service. Hard handoff is used by the systems which use time division multiple access (TDMA) and frequency division multiple access (FDMA) such as GSM and General Packet Radio Service (GPRS) (Leu and Mark, 2002).

In contrast to hard handoff, a soft handoff can establish multiple connections with neighboring cells. Soft handoff is used by the code division multiple access (CDMA) systems where the cells use same frequency band using different code words. Each MS maintains an active set where BSs are added when the RSS exceeds a given threshold and removed when RSS drops below another threshold value for a given amount of time specified by a timer. When a presence or absence of a BS to the active set is encountered soft handoff occurs. The sample systems using soft handoff are Interim Standard 95 (IS-95) and Wideband CDMA (WCDMA) (Pollioni, 1996), (Tripathi et al., 1998) and (Leu and Mark, 2002).

Brusic and Hendling (Brusic and Hendling, 2001) proposed a handoff algorithm based on neighboring cells capacity instead of using the strongest RSS. The call or data connection is handed off to the cell with lower capacity and whose RSS is higher then a specified threshold.

2.7.2 Microcellular vs. Multilayer Handoff

In this section, we will first look at the handoff issues in microcellular environments. Later, we will investigate some systems that use microcells overlaid by macrocells in order to minimize number of handoffs.

2.7.2.1 Microcellular Handoff

The microcells are cells with small radii and employed in highly populated areas such as city buildings and streets to meet high system capacity by frequency reuse. In Fig. 2.2, we have two streets intersecting with three BSs employed on the streets. BS1 and BS3 have line-of-sight (LOS) with each other. The handoff between BS1 and BS3 is called LOS handoff; on the other hand the handoff between BS1 and BS2 is a non-LOS (NLOS) handoff since they don't have LOS (Pollioni, 1996), (Tripathi et al., 1998) and (Leu and Mark, 2002). In NLOS handoffs, when a MS lose LOS (by turning the corner) with current BS, a drop in RSS (20-30 dB) occurs (Tripathi et al., 1998), (Leu and Mark, 2002). This effect is called corner effect and needs faster handoff algorithms since the RSS can drop quickly below the receiver threshold resulting in a call drop. Two types of handoffs, LOS and NLOS, have different characteristics where LOS handoffs try to minimize the number of unnecessary handoffs between BSs and NLOS must be as quickly as possible because of the corner effect.

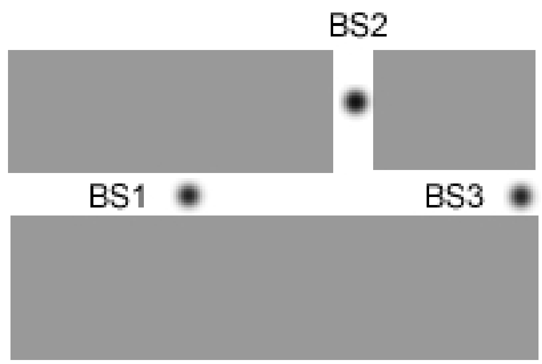

Figure 2.2 A city segment with three BSs deployed on streets.

In (Leu and Mark, 2002), a fast handoff algorithm for hard handoffs is proposed to remove fast fading fluctuations resulting in algorithm that reacts more quickly to corner effect. They propose a technique called local averaging, in which the averaging time interval is smaller than averaging time interval of common handoff algorithms and improve handoff performance. The authors proposed an improved version of the algorithm by adding a drop timer to local averaging technique which decreases the unnecessary handoffs (Leu and Mark, 2003). Then, they compare their proposal with a common averaging technique which uses an exponential window.

A direction biased algorithm is proposed in (Austin and Stüber, 1994) where all the BSs in handoff decision are grouped in two groups. One set of BSs are those in which MS is approaching and the other set includes the BSs in which the MS moves away. In handoff initiation an encouraging hysteresis (h_e) is used to first group where a discouraging hysteresis (h_d) is applied to the second one. The relation between these hysteresis values is $h_e \leq h \leq h_d$. A signal strength based direction estimation method is used for determining the mobile positions.

2.7.2.2 Multilayer Handoff

Some designs used a multilayer approach in order to decrease the number of handoffs and to increase system capacity. A number of microcells are overlaid by a macrocell and the users are assigned to each layer according to their speeds. The microcells and macrocells coverage area are about 500 meters and 35 km, respectively for GSM900 in (Naslund et al., 1998). Since slow users are assigned to the microcells and fast users are assigned to the macrocells, the total number of handoff requests is decreased. Macrocells not only serve the fast users but also serve slow users when the microcells are congested. When a microcell allocates all of its channels, the new and handoff calls are overflowed to the macrocell layer. When the microcells load decreases it is possible to assign the slow users a channel in the microcell. This type of handoff is called take-back. So far, we have four types of handoffs: microcell-to-microcell, microcell-to-macrocell, macrocell-to-macrocell, and macrocell-to-microcell (Tripathi et al., 1998).

In (Ramsdale and Harrold, 1992), a two-layer system is proposed for GSM phase 2 which uses microcells to increase the system capacity. The cell selection for fast and slow users is determined by a switching parameter and cell selection penalty.

In (Iera et al., 2002), a bonus-based algorithm is proposed where it is compared with classical and macro algorithms. In the classical algorithm, in the case of new call request, a user is assigned to a microcell or overflowed to a macrocell if the capacity of the microcell is full. After the user speed estimation is done, the user is assigned to the appropriate layer using overflow and take-back. This scheme results in too many handoffs known as the ping-pong effect. The macro algorithm is similar to the classical algorithm with one exception. When a user is assigned to the macrocell it is not permitted to be taken-back to the microcell which decreases the number of handoffs. The bonus-based algorithm tries to prevent unnecessary handoffs to the microcell when fast users temporarily slow down. For each fast user a time bonus is given and the user can use this time bonus during temporary slow downs. If a user exceeds the timer then it is assigned as a slow user and is taken-back to the microcell layer.

A speed-sensitive handoff algorithm is proposed by Vakili and Aziminejad (Vakili and Aziminejad, 2003) where slow users are assigned to microcells and fast users to the macrocells. The algorithm provides both overflow and take-back of a call when the MS with corresponding layer can not find an unoccupied channel. For example, when a fast user requests a channel from a macrocell; macrocells hand-downs a slow user to the microcell if no free channel is available.

Hu and Rappaport (Hu and Rappaport, 1995) also described and proposed a model for three-layer hierarchical network consisting of microcells, macrocells, and spot beams. Microcells and macrocells are terrestrial part of the network whereas spot beams correspond to satellite part. The users can be overflowed from lower layers to the upper layers but take-back is not allowed.

In future systems, global coverage can be achieved using Hierarchical Cell Structure (HCS) where the HCS has picocells at the lowest layer for indoor communications (Ekici and Ersoy, 2001) with higher data rates and the rest of the layers are as those described by (Hu and Rappaport, 1995). Ekici and Ersoy (Ekici and Ersoy, 2001) also present a probabilistic optimization technique using simulated annealing approach to determine the system parameters for achieving minimum system cost of a multi-tier cellular network.

In (Benveniste, 1995), a cell selection for slow and fast users is introduced using a time offset. If a user resides in the cell at least offset time then it is assigned as slow user. Otherwise, it is assigned as a fast user and sent to macrocell. The time offset is increased and the signal threshold for initiating the time offset is reduced in order to increase the efficiency of the cell selection mechanism.

2.7.3 Horizontal vs. Vertical Handoff

Handoff between homogenous networks where one type of network is considered is called horizontal handoff. On the other hand, handoff between different types of networks is also possible. A handoff in such a heterogeneous environment is named vertical handoff (Stemm and Katz, 1999).

2.8 PRIORITIZATION SCHEMES

In non-prioritization schemes new calls and handoff calls are treated the same way. When a BS has an idle channel, it is assigned due to first-come first-serve basis regardless of whether the call is new or handoff. But, forced termination of an active call is less desirable by the cellular users in contrast to new call blocking (Tekinay and Jabbari, 1991), (Tekinay and Jabbari, 1992), (Agrawal et al., 1996). In order to provide lower forced termination probability, prioritization schemes assigns more channels to the handoff calls. The two well-known prioritization schemes are: guard channels and queuing handoff calls (Tekinay and Jabbari, 1991), (Marichamy et al., 1999), (Tripathi et al., 1998) and (Tekinay and Jabbari, 1992).

The guard channel scheme reserves some fixed or adaptively changing number of channels for handoff calls only. The rest of the channels are used by new and handoff calls. So, the handoff calls are better served and forced termination probability is decreased. The costs of such a scheme are an increase in call blocking probability and a decrease in total carried traffic.

In (Agrawal et al., 1996) the number of guard channels is determined dynamically by the use of neighboring BSs. Each BS determines the number of MSs in pre handover zone (PHZ) periodically and informs its neighbor BS related to that PHZ. PHZ is a small area located next to handoff zone and contains the possible users that will enter handoff zone soon. When the BS gets the number of MSs in PHZ it reserves that amount of guard channels for handoff calls. A new call is assigned a channel if no handoff calls are queued in the queue where handoff calls are kept and the total number of free channels is greater than the number of guard channels.

Zhang and Liu (Zhang and Liu, 2001) proposed an adaptive algorithm which assigns the number of channels adaptively. When forced termination probability exceeds a predefined threshold the guard channel number is increased to decrease the forced termination probability to a value below the threshold. The number of guard channels is decreased in the case where the BS does not use reserved guard channels significantly.

Queuing handoff calls prioritization scheme queues the handoff calls when all of the channels are occupied in a BS. When a channel is released, it is assigned to one of the handoff calls in the queue. A new call request is assigned a channel if the queue is empty and if there is at least one free channel in the BS. Also, some systems queue new calls to decrease call blocking probability (Choi and Sohraby, 2000). The time interval between handoff initiation and receiver threshold makes it possible to use queuing handoff calls. Queuing handoff calls can be used with/without the guard channel scheme.

In (Marichamy et al., 1999), a timer based handoff priority scheme is proposed. When a channel is released at BS, a timer is started. If a handoff request is done in that time interval it is assigned to it. Otherwise, when the timer expires, the channel can be assigned to new or handoff calls depending on the arrival order.

Tekinay and Jabbari (Tekinay and Jabbari, 1992) introduced a new prioritization scheme called Measurement Based Prioritization Scheme (MBSP). The handoff calls are added to the queue and priorities of the calls changes dynamically based on the power level they have. The calls with power level close to the receiver threshold have the highest priorities. This scheme provided better results from the first-in first-out (FIFO) queuing scheme where the handoff calls are served due to arrival time.

The Most Critical First (MCF) policy described in (Agrawal et al., 1996) determines the first handoff call that will be cut off and assigns the first released channel to that call. The first handoff call that will be cut off has the highest priority. The authors proposed a method to predict the first handoff call to be cut off by using simple radio measurements.

In (Choi and Sohraby, 2000), a queuing scheme using guard channels is described. Both new calls and handoff calls are queued. A number of guard channels are reserved for handoff calls. When the new calls are congested, a channel from the guard channels is used if it is available. This scheme decreases the call blocking probability while increasing forced termination probability slightly.

Salih and Fidanboylu (Salih and Fidanboylu, 2003), (Salih and Fidanboylu, 2004) described and modeled queuing techniques for two-tier cellular networks. In (Salih and Fidanboylu, 2003), a microcell/macrocell network using a FIFO queue in macrocell tier and in (Salih and Fidanboylu, 2004) a microcell/macrocell network using a FIFO queue in microcell tier is introduced and compared with each other. The results of both systems showed that forced termination probability for slow users is decreased when the FIFO queue is used in the microcell and forced termination for fast users is decreased when the queue is in the macrocell.

CHAPTER 3

SINGLE AND TWO TIER NETWORK MODELS

3.1 INTRODUCTION

In this chapter three types of networks are investigated: a single-tier network with FIFO queue, a two-tier network with FIFO queues in microcell or macrocell, and a two-tier network with guard channels in microcell or macrocell. Since two-tier networks have both microcells and macrocells and a macrocell can cover a number of microcells, two types of users are assigned to the appropriate layer due to their speeds to decrease handoff call blocking probability by decreasing the number of crossing between cells. Slow users are assigned to microcells and the fast users are assigned to macrocells, respectively.

In this study, we assume that the type of the user is known when the user requests a new call or handoff call request. Slow speed users are assigned first to the microcell, however if there is no free channels and the queue is full then the new call and handoff call requests are overflowed to the macrocell. When some channels are freed in the microcell, it is possible to take slow user back (take-back) to the microcell as discussed in Section 2.9. In this work no take-back is allowed as in (Iera et al., 2002) because of its increased system complexity even when the fast users in the macrocell layer become slow speed users.

Releasing a channel is possible in two cases: First the user completes its call successfully and releases the channel and second the ongoing call is blocked due to a handoff failure. When the mobile station sends a handoff request, the call can be blocked in two ways: When the queue in the neighboring cell is full and the user's RSS level drops below the "receiver threshold" while waiting in the queue. In the case of guard channels, the handoff call is blocked when all the channels are occupied. The handoff requests of slow speed users are overflowed to the macrocell in the case of handoff blocking.

In the case of new calls, the call is blocked when there are no free channels in cell for queued networks. The new calls can be blocked in the networks using guard channels even though the cell has some free channels. If the number of free channels is less than the guard channel size c_h than the new calls are blocked to give higher priority to the handoff calls. The new call requests of slow speed users are overflowed to the macrocell in the case of new call blocking.

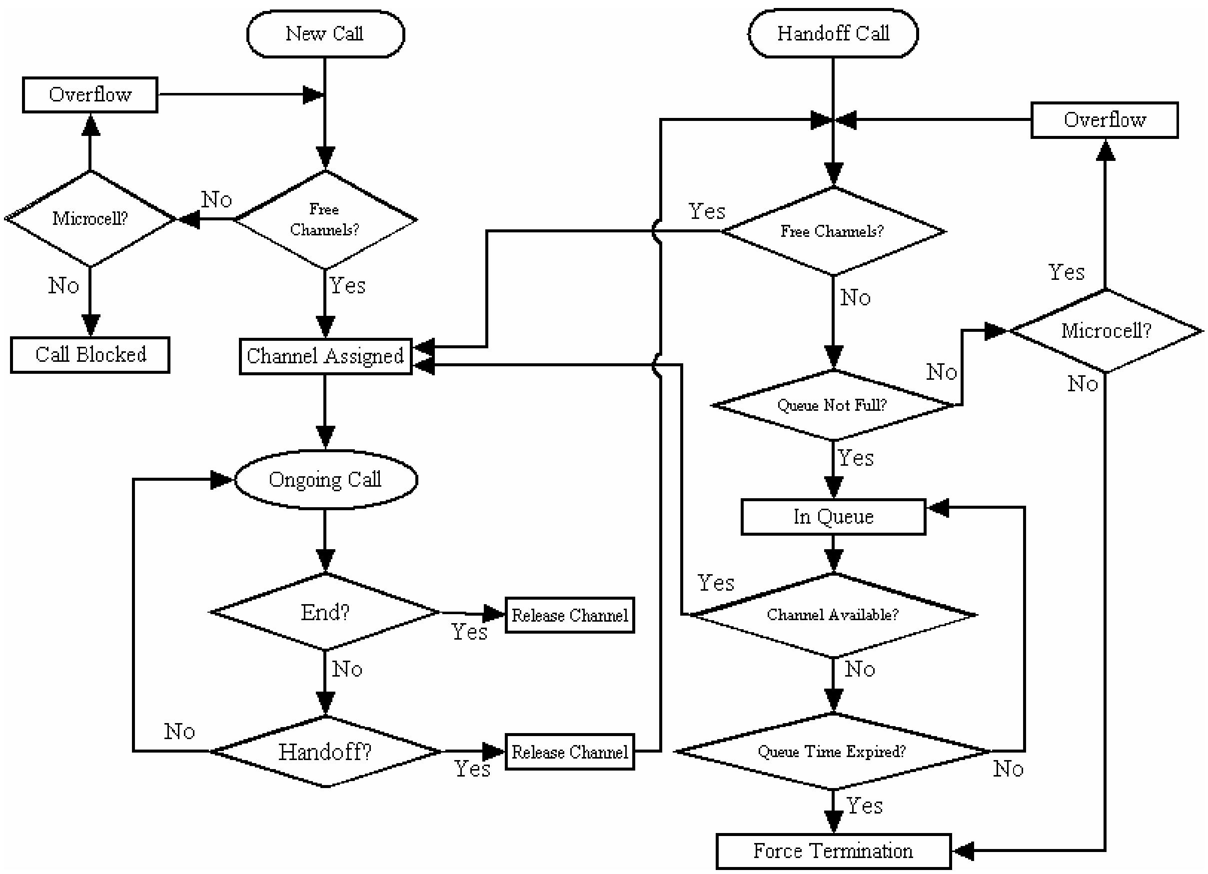

Figure 3.1 Call flow diagram for a cellular network with a FIFO queue.

The call flow diagram for a two-tier cellular network with FIFO queue in microcell/macrocell is presented in the Fig. 3.1. The system behavior of such a network for both types of users is described below:

- The new call of a low speed user is first assigned to the microcell where the MS is covered. If there is at least one free channel, a channel is assigned to the low speed user in the microcell. If no free channels exist in the microcell, the call is overflowed to the macrocell covering this microcell. The call is blocked if macrocell also has no free channels.

- The new call of a high speed user is assigned to the macrocell where the MS resides. If there is at least one free channel, a channel is assigned to the call, otherwise, it is blocked.

- The handoff call of a low speed user is first directed to the neighboring microcell. If no free channels are available the call is put in to the queue provided that a queue exists in the microcell. If no queue exists in microcell, the call is overflowed to the macrocell. A channel is assigned if a free channel exists. Otherwise, the same technique is used as in microcell provided that a queue is presented in macrocell. When a channel is released, a handoff call in the queue is assigned to the channel. When the queue time of a call expires (the received signal is not sufficient), the call is forced to terminate.

- The handoff call of a high speed user is directed to the neighboring macrocell and a channel is acquired if at least one free channel exists. When all the channels are assigned, the call is put into the queue provided that a queue is presented. The call is forced to terminate when there is no queue and all channels are busy or the queue time of the handoff call expires before a channel is acquired.

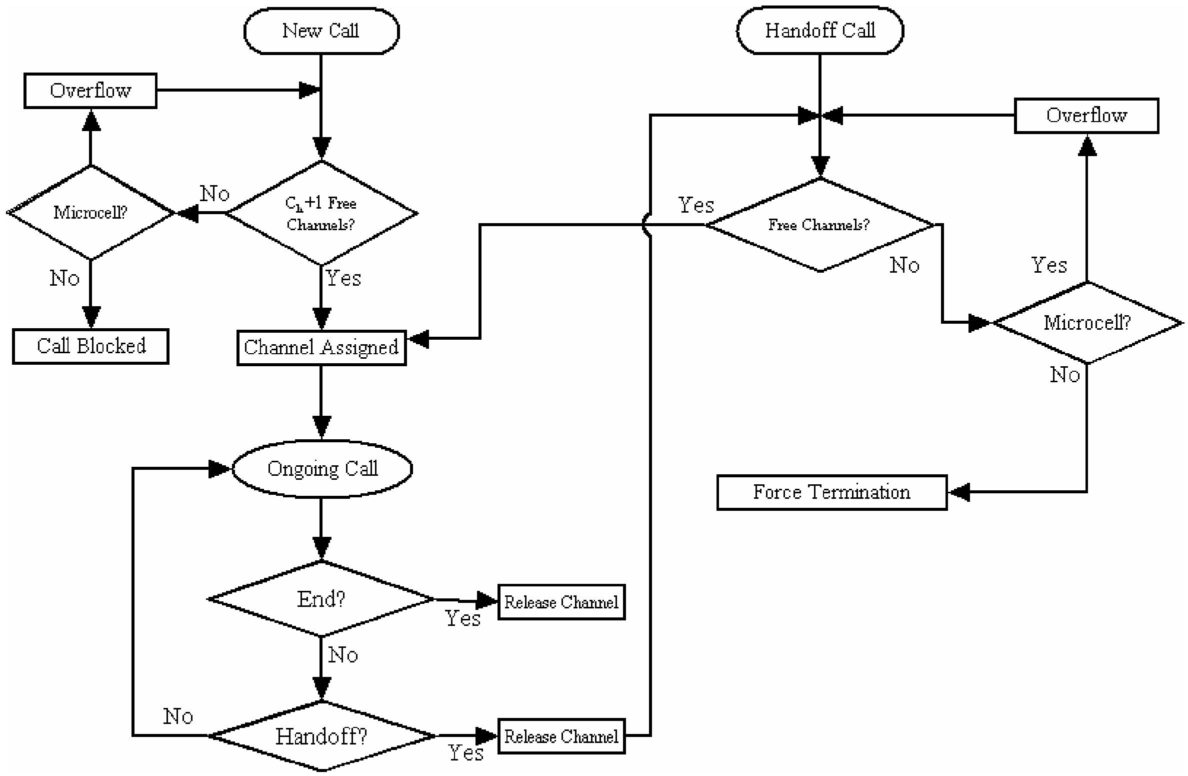

Figure 3.2 Call flow diagram for a cellular network with guard channels.

The call flow diagram for a two-tier cellular network with guard channels in microcell/macrocell is presented in the Fig. 3.2. The system behavior of such a network for both types of users is described below:

- The new call of a low speed user is first assigned to the microcell where the MS is covered. If there are more than c_h free channels in the cell, a channel is assigned to the low speed user in the microcell. If no free channels or less than c_h channels exist in the microcell, the call is overflowed to the macrocell covering this microcell. The call is blocked if the same scenario of the microcell is presented in the macrocell.

- The new call of a high speed user is assigned to the macrocell where the MS resides. If there is at least one free channel, a channel is assigned to the call, otherwise, it is blocked.

- The handoff call of a low speed user is first directed to the neighboring microcell. If no free channels are available the call is overflowed to the macrocell. A channel is assigned if a free channel exists either in microcell or macrocell. The call is blocked if all the channels in the macrocells are occupied.

- The handoff call of a high speed user is directed to the neighboring macrocell and a channel is acquired if at least one free channel exists. The call is forced to terminate when all channels are busy.

This chapter is divided into several sections. In Section 3.2 the model assumptions for overall system is presented. In Sections 3.3 and 3.4, single tier cellular network models with FIFO queue are presented for single and two type user classes. Then, network models for two tier cellular networks with queue in macrocell/microcell are developed in Sections 3.5 and 3.6. Finally, network models for two tier cellular networks with guard channels in macrocell/microcell are presented in Sections 3.7 and 3.8.

3.2 MODEL ASSUMPTIONS

All the network models are proposed due to a single cell model in the network where all the cells are considered to be homogeneous and in equilibrium at the steady-state of the network. The overall system can be studied and analyzed using one cell in each layer as in (Hu and Rappaport, 1995).

The following assumptions are general assumptions for the network models and are changed due to the model and user type slightly:

All the cells are assumed to be circular in shape and N microcells are covered by a macrocell as in (Salih, 2003).

1. Each microcell has c channels and each macrocell has C channels.
2. A microcell can have a queue of size q and a macrocell can have a queue with size Q.

3. A microcell can have c_h guard channels where the macrocell can have C_h guard channels.

4. New call arrival rate for low speed users follow a Poisson process with rate λ_l calls per second.

5. New call arrival rate for high speed users follow a Poisson process with rate λ_h calls per second.

6. Handoff call arrival rate for low speed users follow a Poisson process with rate λ_{hl} calls per second.

7. Handoff call arrival rate for high speed users follow a Poisson process with rate λ_{hh} calls per second.

8. New call arrival rate for low speed users to the macrocell layer follow a Poisson process with rate λ_{ol} calls per second.

9. Handoff call arrival rate for low speed users to the macrocell layer follow a Poisson process with rate λ_{olh} calls per second.

10. The average call holding time for both types of users is negatively exponentially distributed with a mean of $1/\mu$.

11. The cell dwell time for low speed users is negatively exponentially distributed with a mean of $1/\mu_{dl}$.

12. The cell dwell time for high speed users is negatively exponentially distributed with a mean of $1/\mu_{dh}$.

13. The queue time for low speed users is negatively exponentially distributed with a mean of $1/\mu_{ql}$.

14. The queue time for high speed users is negatively exponentially distributed with a mean of $1/\mu_{qh}$.

15. The arrival rate of low speed users to the macrocell when a high speed user becomes a low speed user follows a Poisson process with rate λ_{L2} calls per second.

As in (Salih and Fidanboylu, 2003) and (Salih and Fidanboylu, 2004), queue times for low speed and high speed users are assumed to be different due to their speeds. A low speed user stays in the handoff region longer than its counterpart.

The mean queue time depends on two parameters (Salih, 2003):

1. The mean cell dwelling time ($1/\mu_d$).
2. The maximum cross-distance over the overlapping zone between two cells, which is indicated as *M* of the diameter of a cell.

Queue time = (M / 100) * cell dwelling time. (3.2.1)

The cell dwell time ($1/\mu_d$) is the time that a user stays in the cell and is dependent to the speed of the user and the area of the cell. When the user stays in the cell at duration of dwell time, it is handed off to another cell. The cell dwell time for a circular cell is calculated as follows:

$$\frac{1}{\mu_d} = \frac{\pi * r}{2 * v} \tag{3.2.2}$$

where *r* is the radius of the cell and *v* is the average speed of the mobile user. When the cell is not circular in shape, the dwell time can be calculated using the following formula:

$$\frac{1}{\mu_d} = \frac{\pi * S}{v * L} \tag{3.2.3}$$

where *S* is the area of the cell and *L* is the perimeter of the cell.

3.3 SINGLE-TIER CELLULAR NETWORK WITH A FIFO QUEUE UTILIZED BY SINGLE USER TYPE

In this section a network model for a single-tier cellular network with a FIFO queue utilized by single user type is presented. The network has a FIFO queue to give higher priority to handoff calls and is analyzed using Markov chains as in (Wu, 2001). Each state, *s(i)* represents the number of users holding voice channels including new calls and handoff calls. The network has *c* channels and a FIFO queue of size *q*. When *c* channels are occupied, only handoff calls are served by the cell. The system is shown in Fig. 3.3.

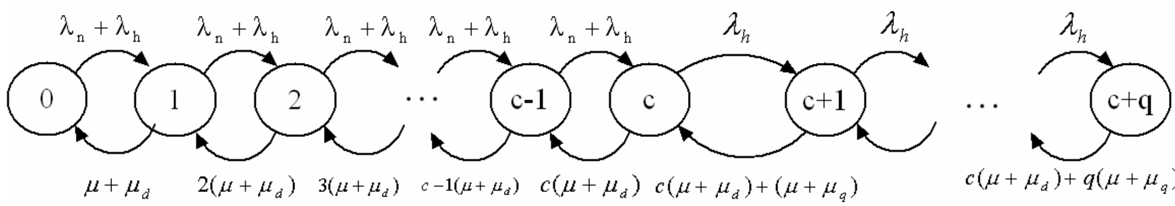

Figure 3.3 Markov chain of the single-tier cellular network with a FIFO queue utilized by single user type.

The steady state probabilities *p(i)* for each state *s(i)* are calculated using

$$p(i) = p_0 \frac{(\lambda_n + \lambda_h)^i}{i!(\mu + \mu_d)^i} \qquad i \le c \tag{3.3.1}$$

$$p(i) = p_0 \frac{(\lambda_n + \lambda_h)^c \lambda_h^{\;i-c}}{c!(\mu + \mu_d)^c \prod_{j=1}^{i-c}\left[c(\mu + \mu_d) + j(\mu + \mu_q)\right]} \qquad i > c \tag{3.3.2}$$

where the total steady state probability is given by

$$\sum_{i=0}^{c+q} p(i) = 1 \tag{3.3.3}$$

A new call is blocked when more than *c* channels are occupied in the cell. On the other hand, a handoff request is blocked when all the channels are used and the queue is full. When the system is in statistical equilibrium the new call blocking probability (P_n), handoff call blocking probabilities (P_h) and handoff dropping probability (P_d) are calculated using the following formulas:

$$P_n = \sum_{i=c}^{c+q} p(i) \tag{3.3.4}$$

$$P_h = p(c+q) \tag{3.3.5}$$

$$P_d = \sum_{i=1}^{q} \frac{i * (\mu_d + \mu_q) * p(c+i)}{\lambda_h} \qquad (3.3.6)$$

The handoff dropping probability given above is calculated as in (Chung and Li, 2005) and (Seo et al., 2004).

As Hu and Rappaport (Hu and Rappaport, 1995) stated that: "For a homogeneous system in statistical equilibrium, the average handoff arrival rate to a microcell should be equal to the handoff departure rate". For the calculation of the handoff departure rate they have presented the following formula:

$$\Lambda_h = \sum_{i=1}^{c} (i * p(i) * \mu_d) \qquad (3.3.7)$$

In order to calculate the handoff arrival rate, an initial value is assigned to handoff arrival rate (λ_h) and handoff departure rate is calculated using the algorithm presented in (Salih, 2003). If handoff arrival and departure are not equal, then handoff arrival is assigned to handoff departure. When both handoff arrival and departure rate becomes equal, we assume that the system is in statistical equilibrium and we obtain the handoff arrival rate. Then, the new call blocking, handoff call blocking and handoff dropping probabilities are calculated using the handoff arrival rate and equations (3.3.4), (3.3.5) and (3.3.6) (Salih, 2003).

Algorithm: **Blocking Probability Calculation**
Input : c, q, λ_n, new λ_h, λ_h, μ, μ_d, μ_q
Output : P_n, P_h, P_d

1. Assign an initial value to new λ_h
2. $\lambda_h \leftarrow$ new λ_h
3. Calculate the steady state probabilities, *p(i)* by using equation (3.3.1) and (3.3.2)
4. Calculate the new handoff departure rate by using equation (3.3.7) and assign it to new λ_h
5. If λ_h is not equal to new λ_h go to step 2
6. Calculate P_n, P_h, P_d using equations (3.3.4), (3.3.5) and (3.3.6)
7. Output P_n, P_h, P_d

3.4 SINGLE-TIER CELLULAR NETWORK WITH A FIFO QUEUE UTILIZED BY TWO TYPES OF USERS

In this section a network model for single-tier cellular network with a FIFO queue utilized by two types of users (low speed and high speed) is presented. Two types of users exist: low speed users and high speed users. The system is analyzed as in (Salih, 2003). Each state *s(i, j, k)* represents the number of ongoing calls of low speed users (*i*), high speed users (*j*) in the cell and the number of handoff calls waiting in the queue (*k*). Since there is no a macrocell layer covering the microcells, there will not be any overflow from a microcell to a macrocell. The system modeled using 2-D Markov chain is shown in Fig. 3.4.

The following equations are used to simplify the model:

$$L = \lambda_l + \lambda_{lh}$$
$$H = \lambda_h + \lambda_{hh}$$
$$M1 = \mu + \mu_{dl}$$
$$M2 = \mu + \mu_{dh}$$
$$M3(i, j, k) = (\lambda_{lh} * j * M2) / (\lambda_{lh} + \lambda_{hh})$$
$$M4(i, j, k) = k(M1q * \lambda_{lh} + M2q * \lambda_{hh}) / (\lambda_{lh} + \lambda_{hh}) + (\lambda_{hh} * j * M2 + \lambda_{lh} * i * M1) / (\lambda_{lh} + \lambda_{hh})$$
$$M5(i, j, k) = (\lambda_{hh} * i * M1) / (\lambda_{lh} + \lambda_{hh})$$
$$M1q = \mu + \mu_{ql}$$
$$M2q = \mu + \mu_{qh}$$
$$R = \lambda_{lh} + \lambda_{hh}$$

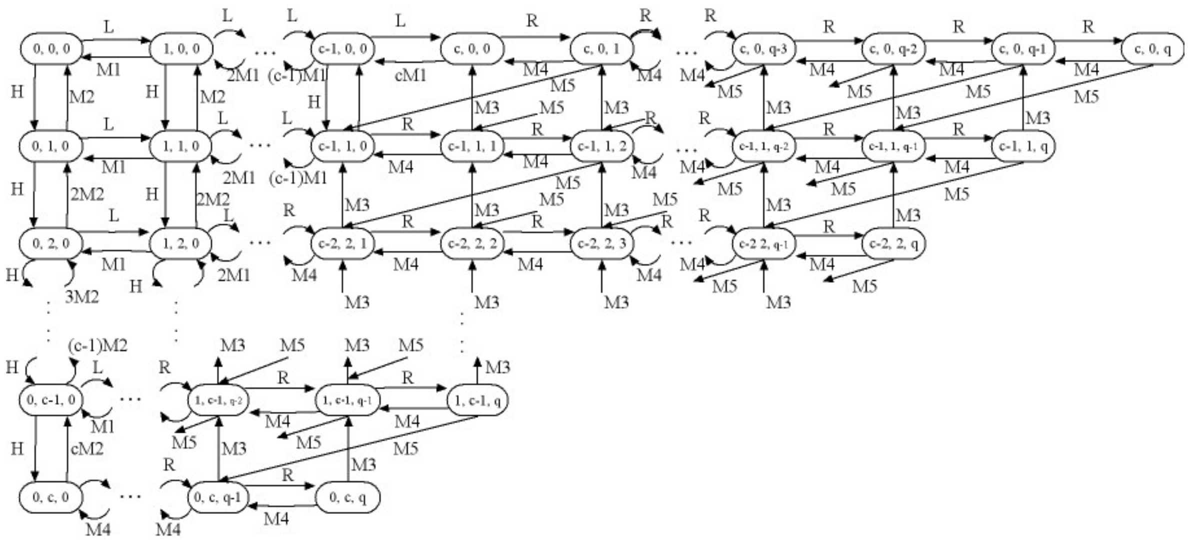

Figure 3.4 2-D Markov chain of the single tier cellular network with a FIFO queue utilized by two types of users.

The following inclusion functions are defined as in (Chiu and Bassioni, 2000) in order to find the equilibrium equation of the state probabilities of 2-D Markov chain:

$$\alpha(i,j,k)=\begin{cases}1 & (i+j\neq c)\,\&\&(k=0)\\ 0 & else\end{cases}$$

$$\beta(i,j,k)=\begin{cases}1 & (i\neq 0)\,\&\&(k=0)\\ 0 & else\end{cases}$$

$$\delta(i,j,k)=\begin{cases}1 & (i+j=c)\,\&\&(k\neq q)\\ 0 & else\end{cases}$$

$$e(i,j,k)=\begin{cases}1 & (i+j=c)\,\&\&(k\neq q)\,\&\&(i\neq 0)\\ 0 & else\end{cases}$$

$$w(i,j,k)=\begin{cases}1 & (i+j=c)\,\&\&(k\neq 0)\\ 0 & else\end{cases}$$

$$m(i,j,k)=\begin{cases}1 & (j\neq 0)\,\&\&(k=0)\\ 0 & else\end{cases}$$

$$\gamma(i,j,k)=\begin{cases}1 & (i\neq 0)\,\&\&(k\neq 0)\,\&\&(i+j=c)\\ 0 & else\end{cases}$$

$$z(i,j,k)=\begin{cases}1 & (j\neq 0)\,\&\&(k\neq 0)\,\&\&(i+j=c)\\ 0 & else\end{cases}$$

$$a(i,j,k)=\begin{cases}1 & (j\neq 0)\,\&\&(k\neq q)\,\&\&(i+j=c)\\ 0 & else\end{cases}$$

Using those inclusion functions, the equilibrium equation for the state occupancy probabilities *p(i, j, k)* is given by

$$p(i,j,k)\begin{bmatrix}\alpha(i,j,k)*(L+H)+\beta(i,j,k)*i*M1+\delta(i,j,k)*R+z(i,j,k)*M3(i,j,k)+\\ w(i,j,k)*M4(i,j,k)+\gamma(i,j,k)*M5(i,j,k)+m(i,j,k)*j*M2\end{bmatrix}=$$
$$\begin{aligned}&\alpha(i,j,k)\left[p(i+1,j,k)*(i+1)*M1+p(i,j+1,k)*(j+1)*M2\right]+\\&\beta(i,j,k)*p(i-1,j,k)*L+\\&m(i,j,k)*p(i,j-1,k)*H+\\&\delta(i,j,k)*p(i,j,k+1)*M4(i,j,k)+\\&e(i,j,k)*p(i-1,j+1,k+1)*M3(i,j,k)+\\&w(i,j,k)*p(i,j,k-1)*R+\\&a(i,j,k)*p(i+1,j-1,k+1)*M5(i,j,k)\end{aligned}$$

The system is solved for the following normalization factor as in (Chung and Li, 2005) iteratively and the handoff arrival rate is calculated in each step:

$$\sum_{i=0}\sum_{j=0}\sum_{k=0} p(i,j,k)=1 \tag{3.4.1}$$

At the end of the steady state calculation, it is observed that the handoff arrival and departure rates are equal as stated by (Hu and Rappaport, 1995). Next, the new call blocking probability, handoff call blocking probability and handoff dropping probabilities for both type of users are found using the following equations:

$$P_n=\sum_{i+j=c} p(i,j,k) \tag{3.4.2}$$

$$P_b=\sum_{i+j=c} p(i,j,q) \tag{3.4.3}$$

$$P_{d\_l}=\sum_{i=1}\sum_{j=1}\sum_{k=1}^{q}\frac{p(i,j,k)*k*(\mu_{dl}+\mu_{ql})*(\lambda_{lh}/(\lambda_{hl}+\lambda_{hh}))}{\lambda_{hl}+\lambda_{hh}} \tag{3.4.4}$$

$$P_{d\_h}=\sum_{i=1}\sum_{j=1}\sum_{k=1}^{q}\frac{p(i,j,k)*k*(\mu_{dh}+\mu_{qh})*(\lambda_{hh}/(\lambda_{hl}+\lambda_{hh}))}{\lambda_{hl}+\lambda_{hh}} \tag{3.4.5}$$

3.5 TWO-TIER CELLULAR NETWORK WITH A FIFO QUEUE IN THE MACROCELL UTILIZED BY TWO TYPES OF USERS

In this section a network model for two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users is presented. The network consists of two layers: a microcell layer and a macrocell layer. Both layers are presented using Markov chains. The microcell layer analysis is similar to the one presented in Section 3.3 which is a single tier network with queue and supports single user type only. The only difference between those two networks is that the microcell layer of this model doesn't have a queue. Taking queue size zero results in current microcell layer of the two tier cellular network with a queue in macrocell. The state transition diagram for microcell layer is as follows:

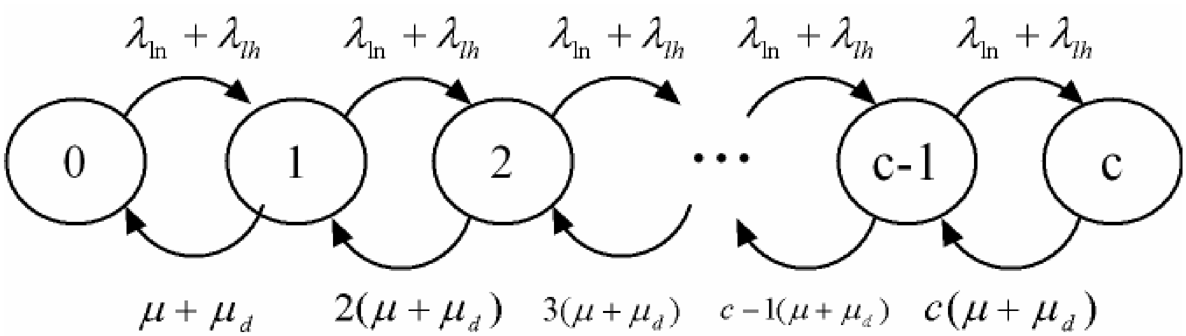

Figure 3.5 State transition diagram for the microcell layer.

The steady state probabilities of the microcell are calculated using the following formula:

$$p(i) = p_0 \frac{(\lambda_{\ln} + \lambda_{lh})^i}{i!(\mu + \mu_d)^i} \quad i \le c \tag{3.5.1}$$

Since the overall systems steady state probabilities sum is $\sum_{i=0} p(i) = 1$, so the $p(0)$ can be written as:

$$p(0) = \left[1 + \sum_{i=1} \left(\frac{(\lambda_{\ln} + \lambda_{lh})^i}{(\mu + \mu_{dl})^i \, i!} \right) \right]^{-1} \tag{3.5.2}$$

The handoff arrival rate for low speed users can be calculated using the algorithm presented in Section 3.3. Since no queue is presented in the microcell, all blocking and dropping probabilities become same and can be found using

$$P_n = P_b = P_d = \sum_{i=c} p(i) = p(c) \tag{3.5.3}$$

After calculating the blocking probabilities for microcell are calculated and we need to calculate the overflow rates for new call and handoff calls of low speed users. The overflow traffic for covering macrocell is calculated as in (Ekici and Ersoy, 2001):

$$\lambda_{ol} = N\lambda_{\ln} P_n \tag{3.5.4}$$

$$\lambda_{olh} = N\lambda_{lh} P_h \tag{3.5.5}$$

Next, we continue with the analysis of the macrocell layer with a FIFO queue as it is shown in Fig. 3.6. The macrocell layer accepts two types of users: low speed and high speed users. The macrocell layer is now similar to the network discussed in Section 3.4 with little modifications; only overflowed traffic from microcell is presented in the macrocell.

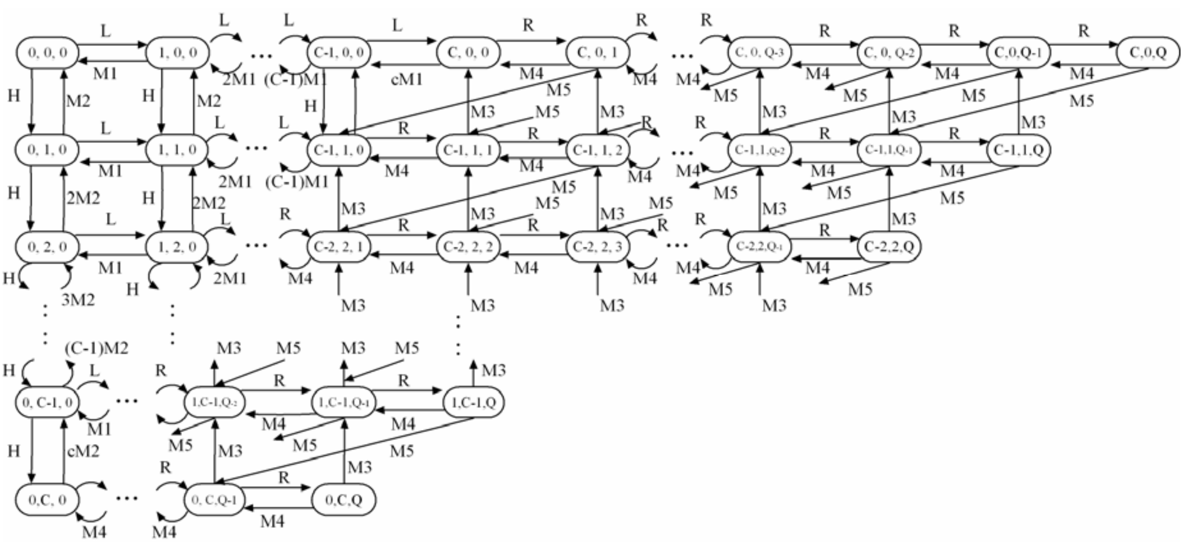

Figure 3.6 2-D Markov chain of the macrocell layer with FIFO queue

The following equations are used to simplify the model:

$$L = \lambda_{ol} + \lambda_{olh} + \lambda_{L2}$$
$$H = \lambda_h + \lambda_{hh}$$

$$M1 = \mu + \mu_{dl}$$
$$M2 = \mu + \mu_{dh}$$
$$M3(i, j, k) = (\lambda_{lh} * j * M2)/(\lambda_{lh} + \lambda_{hh})$$
$$M4(i, j, k) = k(M1q * L1 + M2q * \lambda_{hh})/(L1 + \lambda_{hh}) + (\lambda_{hh} * j * M2 + L1 * i * M1)/(L1 + \lambda_{hh})$$
$$M5(i, j, k) = (\lambda_{hh} * i * M1)/(L1 + \lambda_{hh})$$
$$M1q = \mu + \mu_{ql}$$
$$M2q = \mu + \mu_{qh}$$
$$R = \lambda_{olh} + \lambda_{L2} + \lambda_{hh}$$
$$L1 = \lambda_{olh} + \lambda_{L2}$$

Using the inclusion functions defined in Section 3.4, the equilibrium equation of the state probabilities of 2-D Markov chain is calculated as follows:

$$\begin{aligned}
p(i, j, k)&\begin{bmatrix} \alpha(i, j, k) * (L + H) + \beta(i, j, k) * i * M1 + \delta(i, j, k) * R + z(i, j, k) * M3(i, j, k) + \\ w(i, j, k) * M4(i, j, k) + \gamma(i, j, k) * M5(i, j, k) + m(i, j, k) * j * M2 \end{bmatrix} = \\
&\alpha(i, j, k)\left[p(i+1, j, k) * (i+1) * M1 + p(i, j+1, k) * (j+1) * M2\right] + \\
&\beta(i, j, k) * p(i-1, j, k) * L + \\
&m(i, j, k) * p(i, j-1, k) * H + \\
&\delta(i, j, k) * p(i, j, k+1) * M4(i, j, k) + \\
&e(i, j, k) * p(i-1, j+1, k+1) * M3(i, j, k) + \\
&w(i, j, k) * p(i, j, k-1) * R + \\
&a(i, j, k) * p(i+1, j-1, k+1) * M5(i, j, k)
\end{aligned}$$

The blocking probability for new calls is calculated using

$$P_{bn} = \sum_{i+j=C} p(i, j, k) \qquad (3.5.6)$$

The blocking probability for handoff calls is calculated using

$$P_{bh} = \sum_{i+j=C} p(i, j, Q) \qquad (3.5.7)$$

The handoff dropping probability for handoff calls is calculated using

$$P_{bd\_l} = \sum_{i=1}\sum_{j=1}\sum_{k=1}^{q} \frac{p(i,j,k)*k*(\mu_{dl}+\mu_{ql})*((\lambda_{olh}+\lambda_{L2})/(\lambda_{olh}+\lambda_{L2}+\lambda_{hh}))}{\lambda_{olh}+\lambda_{L2}+\lambda_{hh}} \quad (3.5.8)$$

$$P_{bd\_h} = \sum_{i=1}\sum_{j=1}\sum_{k=1}^{q} \frac{p(i,j,k)*k*(\mu_{dh}+\mu_{qh})*((\lambda_{hh})/(\lambda_{olh}+\lambda_{L2}+\lambda_{hh}))}{\lambda_{olh}+\lambda_{L2}+\lambda_{hh}} \quad (3.5.9)$$

The blocking probabilities, new call blocking, handoff call blocking and handoff dropping probability, for the overall system are calculated using the blocking probabilities of the microcell and macrocell as follows (Wu, 2001):

- P_{bn_h} is the overall new call blocking probability for high speed users
- P_{bh_h} is the overall handoff call blocking probability for high speed users
- P_{d_h} is the overall handoff dropping probability for the high speed users
- P_{bn_l} is the overall new call blocking probability for low speed users
- P_{bh_l} is the overall handoff call blocking probability for low speed users
- P_{d_l} is the overall handoff dropping probability for the high speed users

$$P_{bn\_h} = P_{bn} \quad (3.5.10)$$

$$P_{bh\_h} = P_{bh} \quad (3.5.11)$$

$$P_{d\_h} = P_{bd\_h} \quad (3.5.12)$$

$$P_{bn\_l} = P_{bn} * P_{n} \quad (3.5.13)$$

$$P_{bh\_l} = P_{bh} * P_{h} \quad (3.5.14)$$

$$P_{d\_l} = P_{d} * P_{bd\_l} \quad (3.5.15)$$

3.6 TWO-TIER CELLULAR NETWORK WITH A FIFO QUEUE IN THE MICROCELL UTILIZED BY TWO TYPES OF USERS

In this section, a network model for two-tier cellular network with a FIFO queue in the microcell utilized by two types of users is presented. The network consists of two layers: a microcell layer and a macrocell layer. Both layers are presented using Markov chains. The microcell layer analysis is as same as the one presented in Section 3.3 and only low speed handoff calls are put into the FIFO queue. The state transition diagram for microcell layer is as follows:

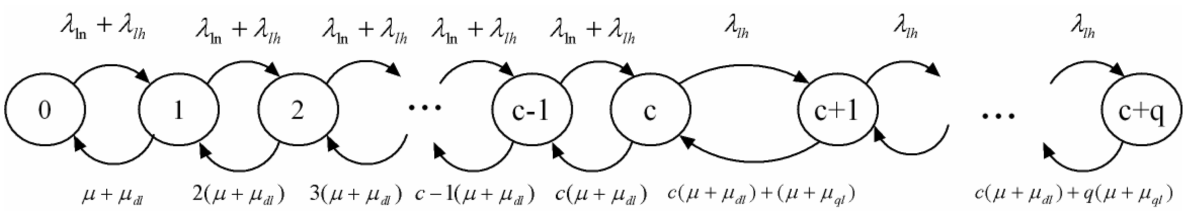

Figure 3.7 State transition diagram of the microcell layer.

The microcell layer is analyzed using single dimensional Markov chains where *i* states the number of low speed users in the microcell in states *s(i)*. When the microcell has *c* ongoing calls, it waits the handoff requests in the queue where the new calls are overflowed to the macrocell.

Again, the steady state probabilities are calculated when the handoff arrival rate for microcell is determined as in Section 3.3 and the new call blocking, handoff call blocking and handoff dropping probabilities are calculated using the state probabilities *p(i),* where they can be calculated using

$$p(i) = p_0 \frac{(\lambda_n + \lambda_h)^i}{i!(\mu + \mu_d)^i} \quad i \le c \tag{3.6.1}$$

$$p(i) = p_0 \frac{(\lambda_n + \lambda_h)^c \lambda_h^{\,i-c}}{c!(\mu + \mu_d)^c \prod_{j=1}^{i-c} \left[c(\mu + \mu_d) + j(\mu + \mu_q) \right]} \quad i > c \tag{3.6.2}$$

The new call blocking probability for low speed users in the microcell is found by

$$P_n = \sum_{i=c}^{c+q} p(i) \tag{3.6.3}$$

The handoff call blocking probability for low speed users in the microcell is calculated by

$$P_h = p(c+q) \tag{3.6.4}$$

The handoff dropping probability for low speed users in the microcell is calculated using:

$$P_d = \sum_{i=1}^{q} \frac{p(c+i) * i * (\mu_{dl} + \mu_{ql})}{\lambda_{lh}} \tag{3.6.5}$$

Next, we need to determine the overflow traffic for both types of calls: new calls and handoff calls of low speed users. The overflow rates for both types of calls are determined using equations (3.5.4) and (3.5.5).

Once we determined the overflow rates, we can continue with the analysis of the macrocell. Now we have a 2-D Markov chain where two types of users are accepted in the macrocell layer. The state transition diagram of 2-D Markov chain is shown in Fig 3.8 and each state *s(i, j)* represents *i* low speed user calls and *j* high speed user calls ongoing.

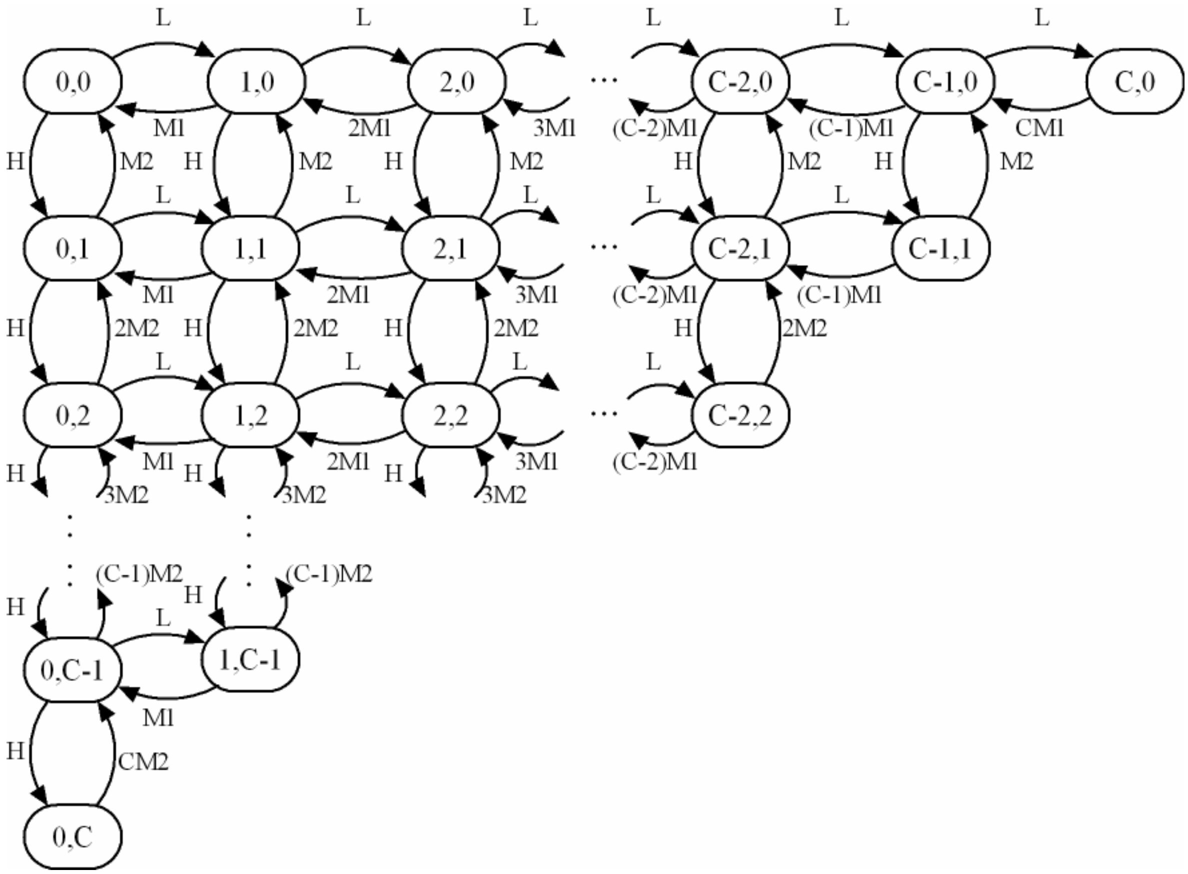

Figure 3.8 State transition diagram of 2-D Markov chain representing macrocell layer.

The following equations are used to simplify the model:

$$L = \lambda_{ol} + \lambda_{olh} + \lambda_{L2}$$
$$H = \lambda_h + \lambda_{hh}$$
$$M1 = \mu + \mu_{dl}$$
$$M2 = \mu + \mu_{dh}$$

Inclusion functions to find the equilibrium equations of the state probabilities are:

$$\alpha(i,j) = \begin{cases} 1 & i + j \le c \\ 0 & else \end{cases}$$
$$\beta(i,j) = \begin{cases} 1 & i \ne 0 \\ 0 & else \end{cases}$$
$$\delta(i,j) = \begin{cases} 1 & j \ne 0 \\ 0 & else \end{cases}$$

Using these inclusion functions, the equilibrium equation for the state occupancy probabilities *p(i, j)* is given by

$$\begin{aligned}
p(i,j)\left[\alpha(i,j)*(L+H)+\beta(i,j)*i*M1+\delta(i,j)*j*M2\right]= \\
\alpha(i,j)\left[p(i,j+1)*(j+1)*M2+p(i+1,j)*(i+1)*M1\right]+ \\
\beta(i,j)*p(i-1,j)*L+ \\
\delta(i,j)*p(i,j-1)*H
\end{aligned}$$

The macrocell layer is solved for the following normalization factor as in (Chung and Li, 2005) iteratively and the handoff arrival rate is calculated in each step as follows:

$$\sum_{i=0}\sum_{j=0} p(i,j)=1 \qquad (3.6.6)$$

The new call blocking, handoff call blocking and handoff dropping probabilities are all same since the macrocell does not have a queue and are calculated by:

$$P_{bn}=P_{bh}=P_{bd}=\sum_{i+j=c} p(i,j) \qquad (3.6.7)$$

The overall system's blocking and dropping probabilities then can be calculated using the equations (3.5.10) through (3.5.15).

3.7 TWO-TIER CELLULAR NETWORK WITH GUARD CHANNELS IN MACROCELL UTILIZED BY TWO TYPES OF USERS

In this section a network model for two-tier cellular network with guard channels in macrocell utilized by two types of users is presented based on (Hu and Rappaport, 1995). The network consists of two layers: a microcell layer and a macrocell layer. Each layer is analyzed separately. Both layers are presented using Markov chains. Instead of having a queue in the macrocell, a number of guard channels are provided in macrocell to decrease handoff call blocking probability. The microcell layer is as same as the microcell layer of cellular network with FIFO queue in macrocell in Section 3.5. The state transition diagram for microcell layer is as follows:

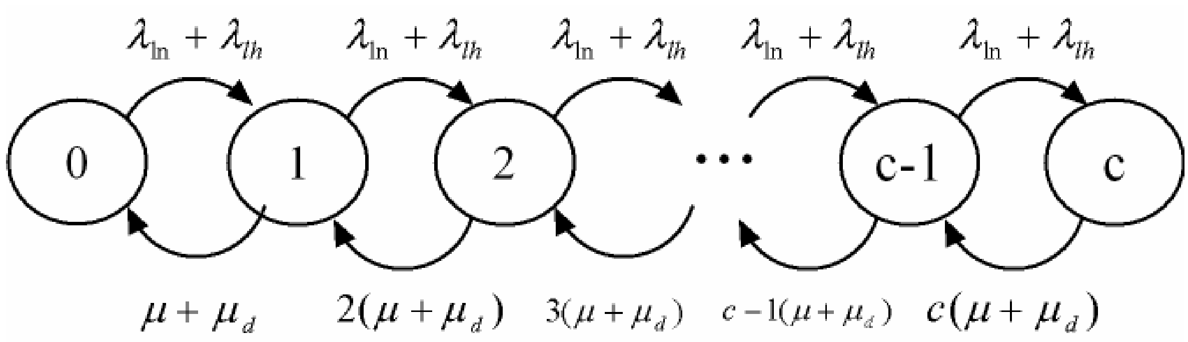

Figure 3.9 State transition diagram of the microcell layer.

The steady state probabilities of the microcell are calculated using the formula

$$p(i) = p_0 \frac{(\lambda_{ln} + \lambda_{lh})^i}{i!(\mu + \mu_d)^i} \quad i \le c \tag{3.7.1}$$

Since the overall systems steady state probabilities total is $\sum_{i=0} p(i) = 1$, the $p(0)$ can be written as

$$p(0) = \left[1 + \sum_{i=1}\left(\frac{(\lambda_{ln} + \lambda_{lh})^i}{(\mu + \mu_{dl})^i i!}\right)\right]^{-1} \tag{3.7.2}$$

The handoff arrival rate for low speed users in microcell can be calculated using the algorithm presented in Section 3.3. All blocking and dropping probabilities are same because of absence of guard channels. The new call blocking probability and handoff call blocking probability for microcell layer can be calculated by

$$P_n = P_b = \sum_{i=c} p(i) = p(c) \tag{3.7.3}$$

The overflow rates for new calls and handoff calls of low speed users are determined using equations (3.5.4) and (3.5.5).

Once we determined the overflow rates, we can continue with the analysis of the macrocell. Now we have a 2-D Markov chain where two types of users are accepted in the macrocell layer. A number of guard channels are presented to give priority to handoff calls of both high speed and low speed users. When the number of available channels is less than C_h, only handoff calls are served. The state transition diagram of 2-D Markov chain is shown in Fig 3.10 and each state *s(i, j)* represents *i* low speed user calls and *j* high speed user calls in conversation.

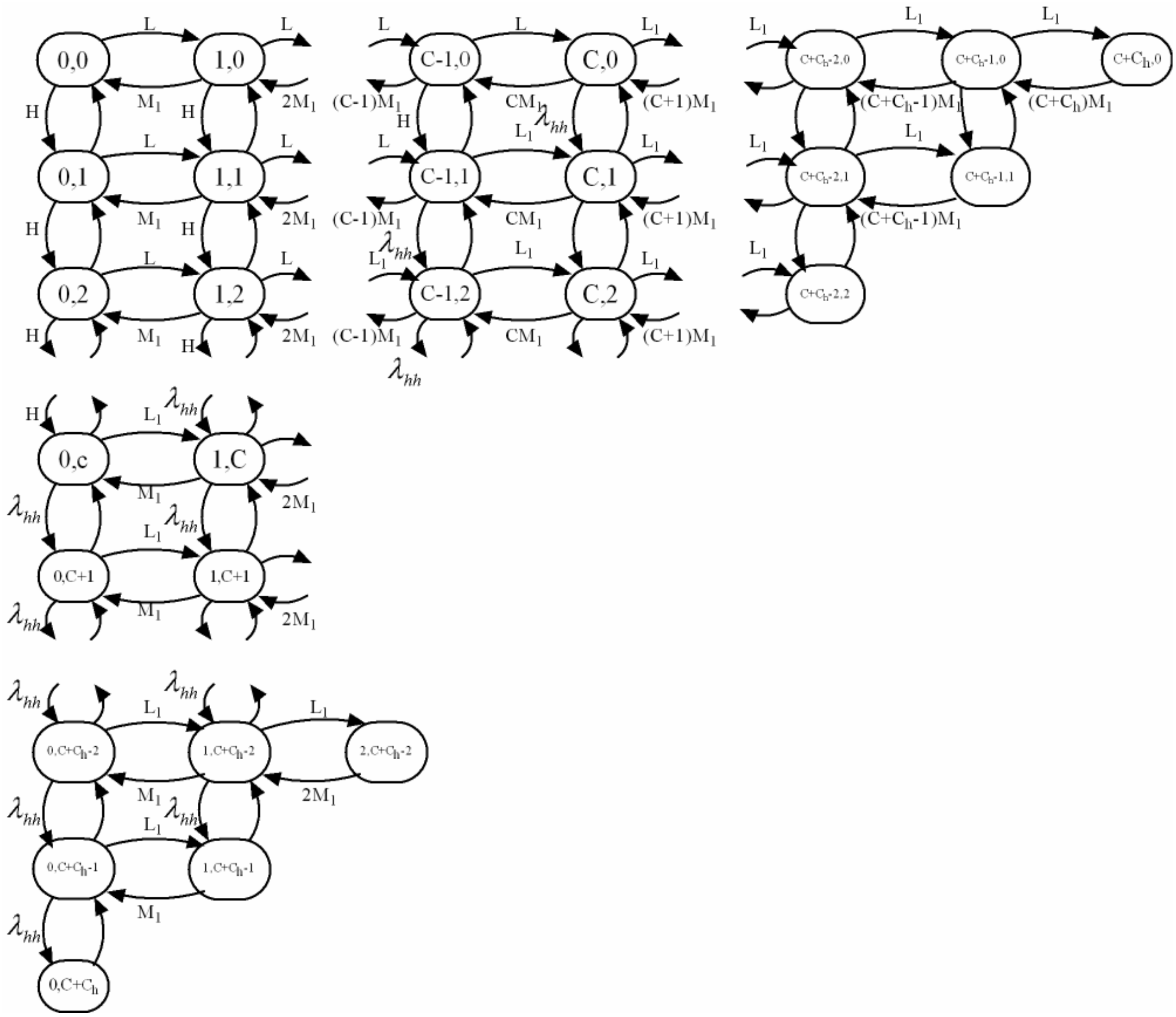

Figure 3.10 State transition diagram of the macrocell layer of two tier network with guard channels in the macrocell.

The following equations are used to simplify the model:

$$L = \lambda_{ol} + \lambda_{olh} + \lambda_{L2}$$
$$H = \lambda_h + \lambda_{hh}$$
$$M1 = \mu + \mu_{dl}$$
$$M2 = \mu + \mu_{dh}$$
$$L1 = \lambda_{olh} + \lambda_{L2}$$

Inclusion functions to find the equilibrium equations of the state probabilities *p(i,j)* are:

$$\alpha(i,j)=\begin{cases}1 & i+j<C\\ 0 & else\end{cases}$$
$$\beta(i,j)=\begin{cases}1 & (i+j\geq C)\,\&\&(i+j<C+C_h)\\ 0 & else\end{cases}$$
$$\delta(i,j)=\begin{cases}1 & (i+j\geq 0)\,\&\&(i+j\leq C+C_h)\\ 0 & else\end{cases}$$

Using these inclusion functions, the equilibrium equation for the state occupancy probabilities *p(i, j)* is given by

$$\begin{aligned} p(i,j)\big[\alpha(i,j)*(L+H)+\beta(i,j)*(L1+\lambda_{hh})+\delta(i,j)*i*M1+\delta(i,j)*j*M2\big]= \\ p(i+1,j)*\delta(i+1,j)*(i+1)*M1+ \\ p(i,j+1)*\delta(i,j+1)*(j+1)*M2+ \\ p(i-1,j)\big[\alpha(i-1,j)*L+\beta(i-1,j)*L1\big]+ \\ p(i,j-1)\big[\alpha(i,j-1)*H+\beta(i,j-1)*\lambda_{hh}\big] \end{aligned}$$

The system is solved for the following normalization factor as in (Chung and Li, 2005) iteratively and the handoff arrival rate is calculated in each step as follows:

$$\sum_{i=0}\sum_{j=0} p(i,j)=1 \tag{3.7.4}$$

The blocking probability for new calls is calculated using

$$P_{bn}=\sum_{i+j=C} p(i,j) \tag{3.7.5}$$

The blocking probability for handoff calls is calculated using

$$P_{bh}=\sum_{i+j=C+C_h} p(i,j) \tag{3.7.6}$$

Since there is no use of a queue, we don't need to calculate the handoff dropping probability in networks using only guard channels because there is no probability of dropping a call waiting in the queue.

The overall system's blocking and dropping probabilities then can be calculated using equations (3.5.10) through (3.5.15).

3.8 TWO-TIER CELLULAR NETWORK WITH GUARD CHANNELS IN THE MICROCELL UTILIZED BY TWO TYPES OF USERS

In this section, a network model for two-tier cellular network with guard channels in the microcell utilized by two types of users is presented based on (Hu and Rappaport, 1995). The network consists of two layers: a microcell layer and a macrocell layer. Each layer is analyzed separately. Both layers are presented using Markov chains. Instead of having a queue in the microcell, a number of guard channels are provided in microcell to decrease handoff call blocking probability. When the number of available channels is less than c_h, only handoff calls are served in microcell. The state transition diagram is shown in Fig 3.11 and each state *s(i)* represents *i* ongoing new and handoff calls of low speed users in the microcell.

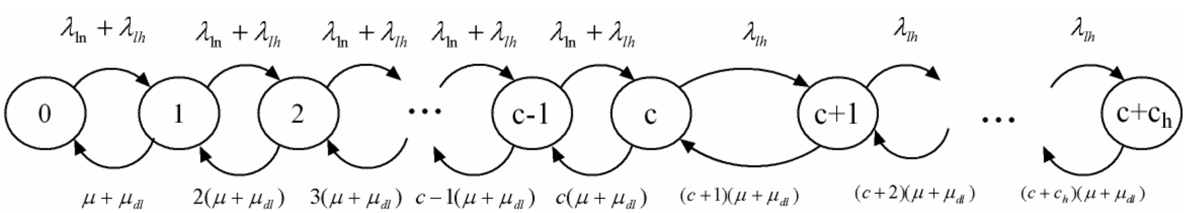

Figure 3.11 State transition diagram of the microcell layer.

The steady state probabilities of the microcell are calculated using the formula:

$$p(i) = p_0 \frac{(\lambda_{ln} + \lambda_{lh})^i}{i!(\mu + \mu_d)^i} \quad i \le c \tag{3.8.1}$$

$$p(i) = p_0 \frac{(\lambda_{ln} + \lambda_{lh})^c \lambda_{lh}^{\,i-c}}{i!(\mu + \mu_d)^i} \qquad i > c \tag{3.8.2}$$

Since the overall systems steady state probabilities total is $\sum_{i=0} p(i) = 1$, the $p(0)$ can be written as:

$$p(0) = \left[1 + \sum_{i=1}^{c} \frac{(\lambda_{\ln} + \lambda_{lh})^i}{i!(\mu + \mu_{dl})^i} + \sum_{i=c+1}^{c+c_h} \frac{(\lambda_{\ln} + \lambda_{lh})^c \lambda_{lh}^{\ i-c}}{i!(\mu + \mu_{dl})^i} \right]^{-1} \quad (3.8.3)$$

The handoff arrival rate for low speed users in microcell can be calculated using the algorithm presented in Section 3.3. The new call blocking probability and handoff call blocking probability for microcell layer can be calculated using

$$P_n = \sum_{i=c}^{c+c_h} p(i) \quad (3.8.4)$$

$$P_h = \sum_{i=c+c_h} p(i) \quad (3.8.5)$$

The overflow rates for new calls and handoff calls of low speed users are determined using equations (3.5.4) and (3.5.5).

Once we determined the overflow rates, we can continue with the analysis of the macrocell. Now we have a 2-D Markov chain where two types of users are accepted in the macrocell layer. No guard channels are presented in macrocell and the state transition diagram is shown in Fig 3.12:

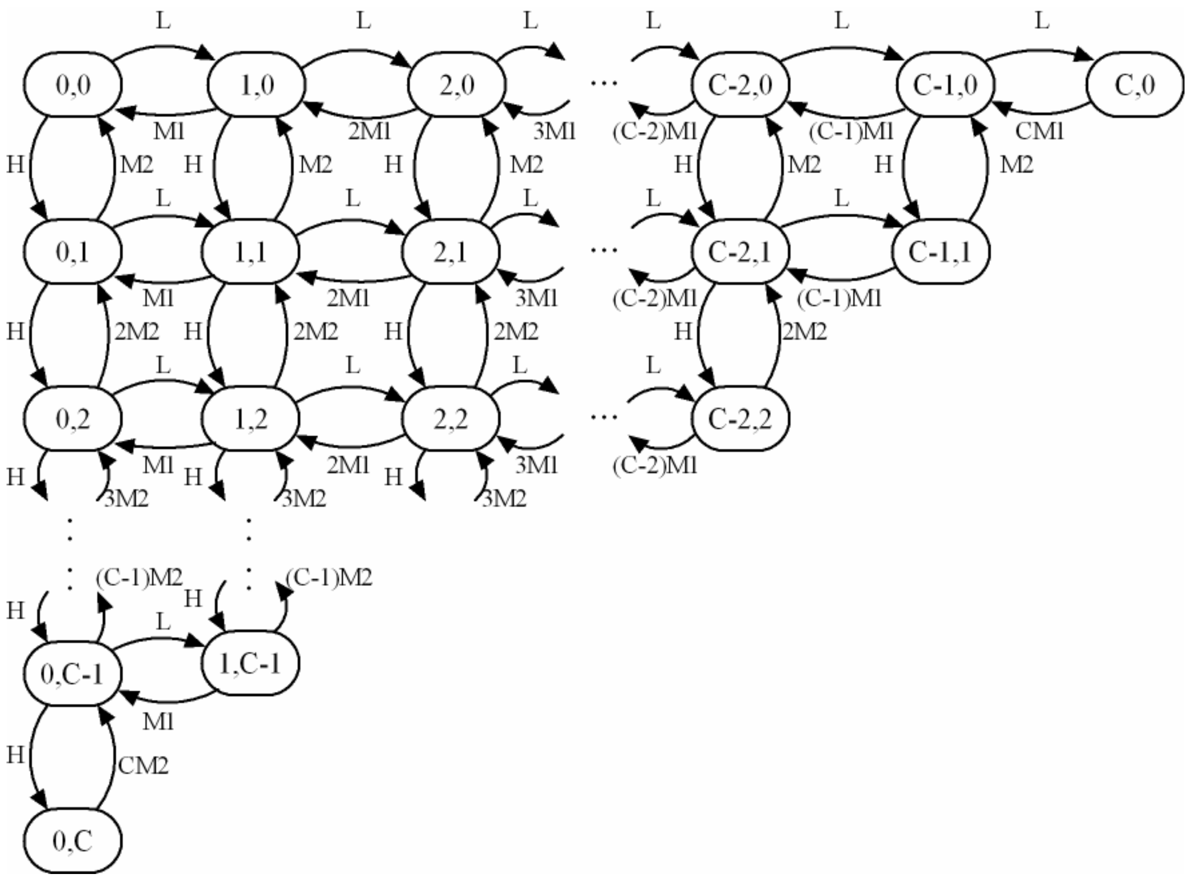

Figure 3.12 State transition diagram of macrocell layer of two tier network with guard channels in the macrocell.

The following equations are used to simplify the model:

$$L = \lambda_{ol} + \lambda_{olh} + \lambda_{L2}$$
$$H = \lambda_h + \lambda_{hh}$$
$$M1 = \mu + \mu_{dl}$$
$$M2 = \mu + \mu_{dh}$$

Inclusion functions to find the equilibrium equations of the state probabilities *p(i,j)* are given by

$$\alpha(i,j) = \begin{cases} 1 & i + j < C \\ 0 & else \end{cases}$$

$$\beta(i,j) = \begin{cases} 1 & i \neq 0 \\ 0 & else \end{cases}$$

$$\delta(i,j)=\begin{cases}1 & j\neq 0\\ 0 & else\end{cases}$$

Using these inclusion functions, the equilibrium equation for the state occupancy probabilities *p(i, j)* is given by

$$\begin{aligned}
p(i,j)\left[\alpha(i,j)*(L+H)+\beta(i,j)*i*M1+\delta(i,j)*j*M2\right]= \\
\alpha(i,j)\left[p(i,j+1)*(j+1)*M2+p(i+1,j)*(i+1)*M1\right]+ \\
\beta(i,j)*p(i-1,j)*L+ \\
\delta(i,j)*p(i,j-1)*H
\end{aligned}$$

The system is solved for the following normalization factor as in (Chung and Li, 2005) and the handoff arrival rate is calculated in each step as follows:

$$\sum_{i=0}\sum_{j=0}p(i,j)=1 \tag{3.8.6}$$

The blocking probabilities for new calls and handoff calls are same and are calculated using

$$P_{bn}=P_{bh}=\sum_{i+j=C}p(i,j) \tag{3.8.7}$$

The overall system's blocking and dropping probabilities then can be calculated using the equations (3.5.10) through (3.5.15).

CHAPTER 4

NUMERICAL RESULTS AND COMPARISONS

4.1 INTRODUCTION

In this chapter, we have used Java programs to calculate the numerical results for the models developed in Chapter 3. The numerical results are plotted using MATLAB to see the effects of each network on the performance parameters: New call blocking probability, handoff call blocking probability and handoff dropping probability. The numerical results of each network are compared for each type of users.

4.2 MODEL PARAMETERS

For the computation of the numerical results, a macrocell covering 7 microcells are assumed for two tier networks. For single tier networks, only a single microcell with 6 neighboring microcells is assumed. A channel size of 28 was assumed in both microcell and the macrocell. The queue size was assumed to be variable between 0 and 6. We also assumed that the user types are known where the low speed users are assigned to the microcell and the high speed users are assigned to the macrocell.

We used the same assumptions used by (Salih, 2003) where the cell dwelling time for low speed users is calculated using the Eq. (3.2.2) and found to be 90 sec. in the microcell and and 238 sec. in the macrocell, respectively. The microcell's diameter is 1.325 km where the macrocell's is 3.5 km. Taking the maximum cross distance of the overlapping zone between two cells as %13 of the diameter of the cell as in (Salih, 2003), we calculated the queue times for low speed users using Eq. (3.2.1). The queue times for low speed users in the microcell and the macrocell are 12 sec. and 31 sec., respectively. Using the same equations, the cell dwelling times for high speed users are 70 sec. in the microcell and 185 sec. in the macrocell, respectively. The queue times in the microcell and macrocell are 9 sec. and 24 sec., respectively. The low speed users have higher queue times than those of high speed users in the same layers because of their low velocity as compared to high speed users.

The mean call holding time for both types of users was assumed to be 180 sec. The new call arrival rates for both types of users is assumed to be same and the arrival rates of handoff calls is calculated using the techniques described in Chapter 3 dynamically.

4.3 NUMERICAL RESULTS FOR SINGLE-TIER CELLULAR NETWORK WITH A FIFO QUEUE UTILIZED BY SINGLE USER TYPE

In this section, the results obtained for a single tier network with a FIFO queue utilized by single user type are presented.

Figure 4.1 shows the new call blocking probability for low speed users in single tier cellular network with FIFO queue utilized by single user type. From this figure it can be observed that the queue size has a slight effect on the new call blocking probability. This is due to the fact that the handoff calls have higher priorities than the new calls in acquiring the free channels.

The handoff call blocking probability for low speed users in single tier cellular network with FIFO queue utilized by single user type is shown in Figure 4.2. This figure shows that as the queue size increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and queue size.

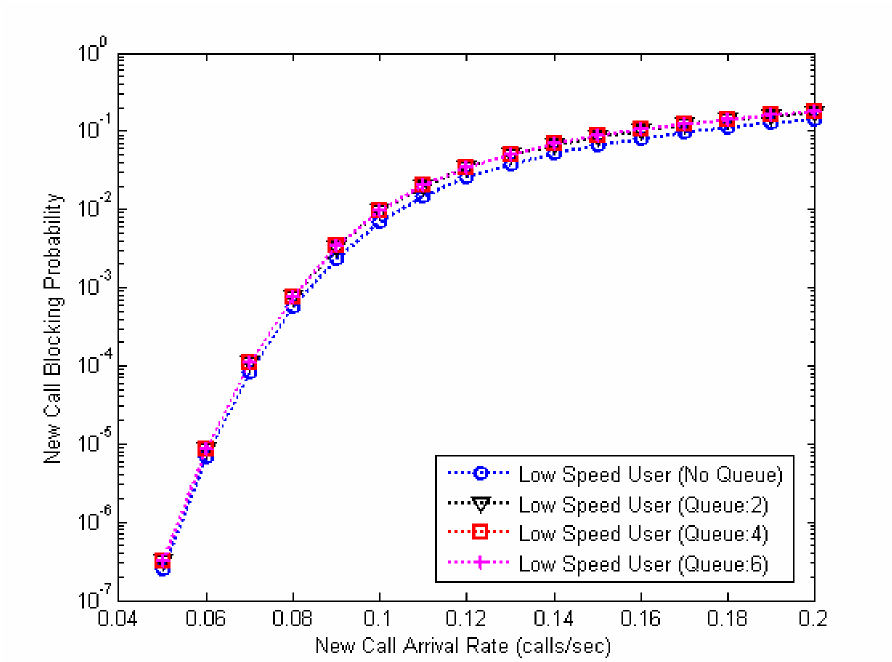

Figure 4.1 New call blocking probability of low speed users with different queue sizes.

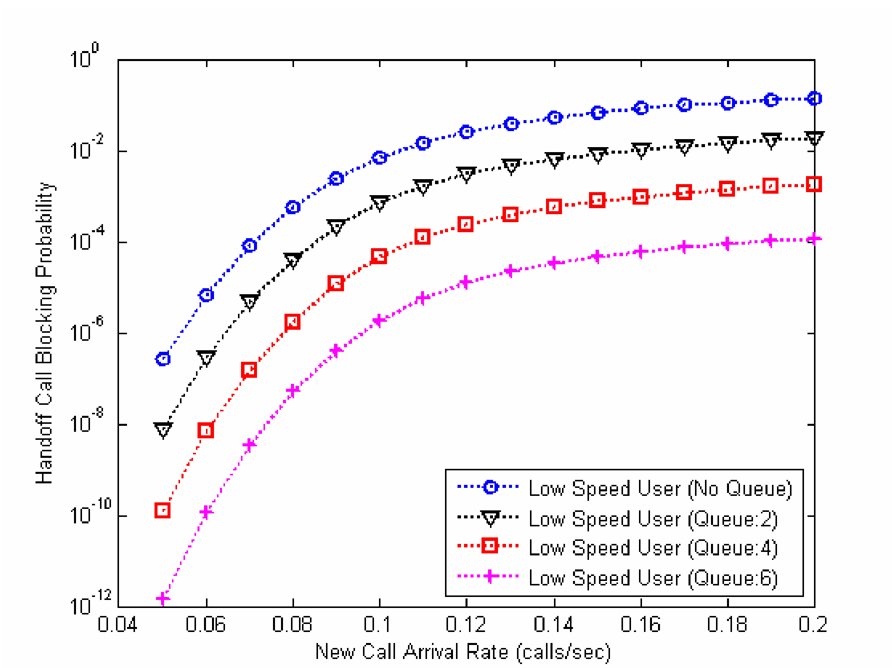

Figure 4.2 Handoff call blocking probability for low speed users with different queue sizes.

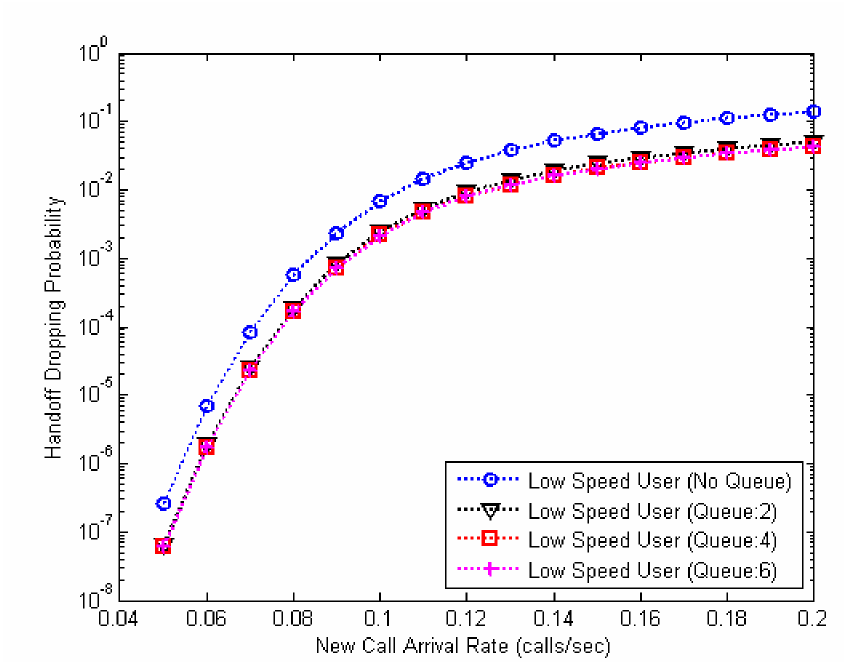

Figure 4.3 Handoff dropping probability for low speed users with different queue sizes.

Figure 4.3 illustrates the handoff dropping probability for low speed users in single tier cellular network with FIFO queue utilized by single user type. The handoff dropping probability decreases slightly as the queue size is increased. However, the overall effect is significantly lower than handoff dropping probability of a network with no queue.

4.4 NUMERICAL RESULTS FOR SINGLE-TIER CELLULAR NETWORK WITH A FIFO QUEUE UTILIZED BY TWO TYPES OF USERS

In this section, the results obtained for a single tier network with a FIFO queue utilized by two types of users are presented. The queue is shared by both types of users.

The new call blocking probability for low and high speed users in single tier cellular network with FIFO queue utilized by two types of users is shown in Figure 4.4. From this figure it can be seen that the queue size has a slight effect on the new call blocking probability. This is due to the fact that the handoff calls have higher priorities than the new calls in acquiring the free channels.

Figure 4.5 shows the handoff call blocking probability for low and high speed users in single tier cellular network with FIFO queue utilized by two types of users. This figure shows that, as the queue size increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect relationship between handoff call blocking probability and queue size.

Figure 4.6 represents the handoff dropping probability for low speed users in single tier cellular network with FIFO queue utilized by two types of users. The handoff dropping probability decreases significantly up to a queue size of 4. However, as queue size increases beyond 4, the handoff dropping probability decreases very slightly.

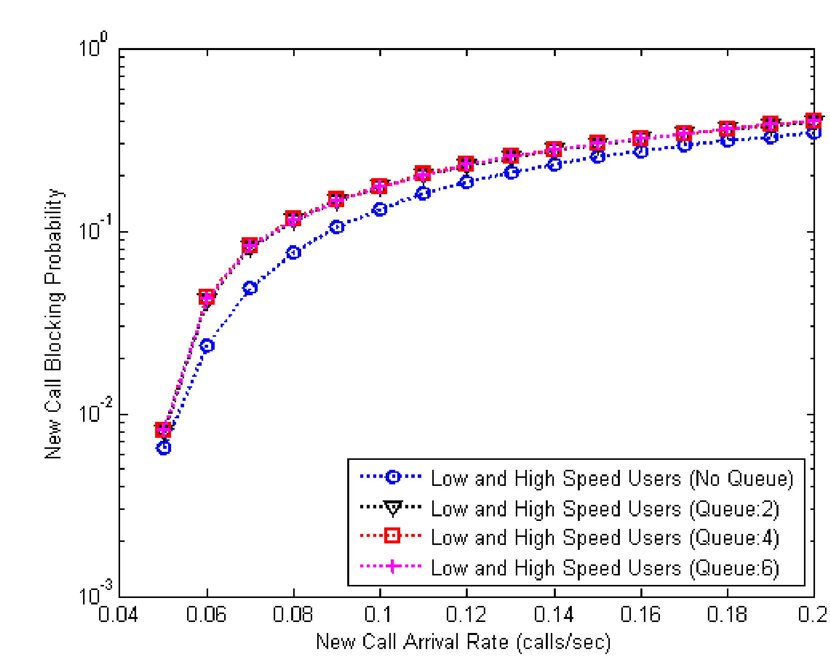

Figure 4.4 New call blocking probability for both user types with different queue sizes.

Similar effect can be observed for the handoff dropping probability for high speed users. The handoff dropping probability for high speed users in single tier cellular network with FIFO queue utilized by two types of users is shown in Figure 4.7.

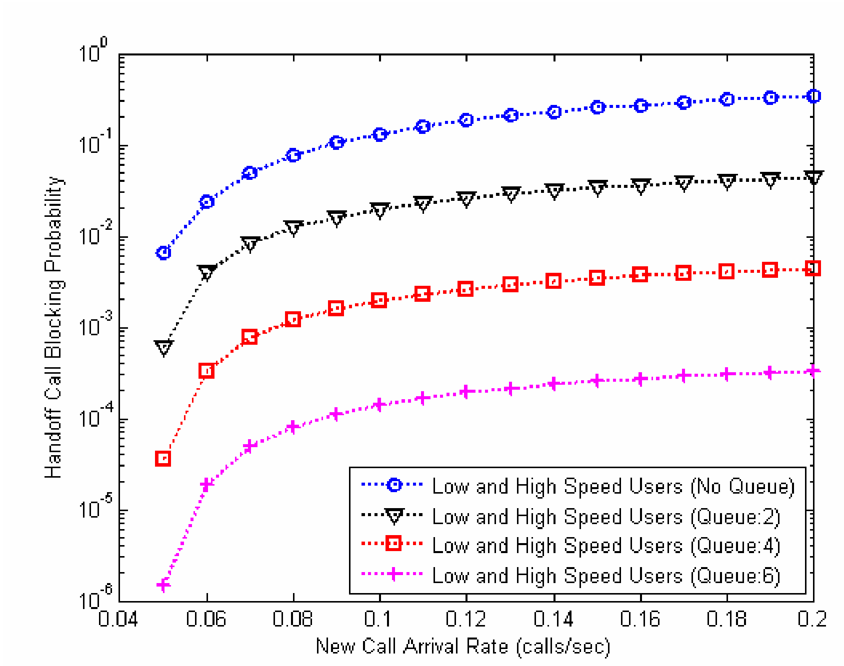

Figure 4.5 Handoff call blocking probability for both user types with different queue sizes.

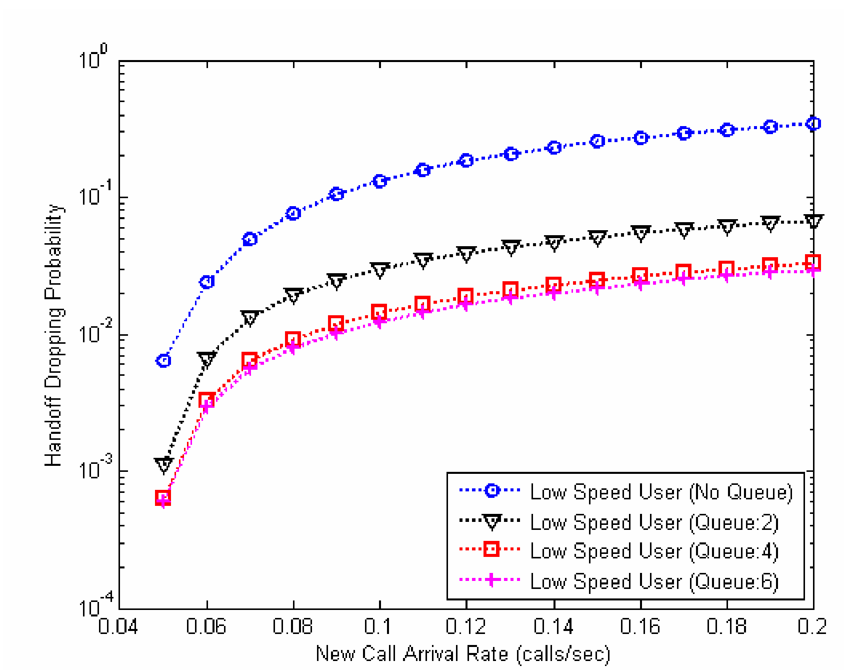

Figure 4.6 Handoff dropping probability for low speed users with different queue sizes.

The comparison of the handoff dropping probability for low and high speed users is presented in Fig. 4.8. Handoff dropping probability for high speed users is higher than the corresponding low speed users. This results from the tendency of a low speed user to stay in the queue longer than a high speed user.

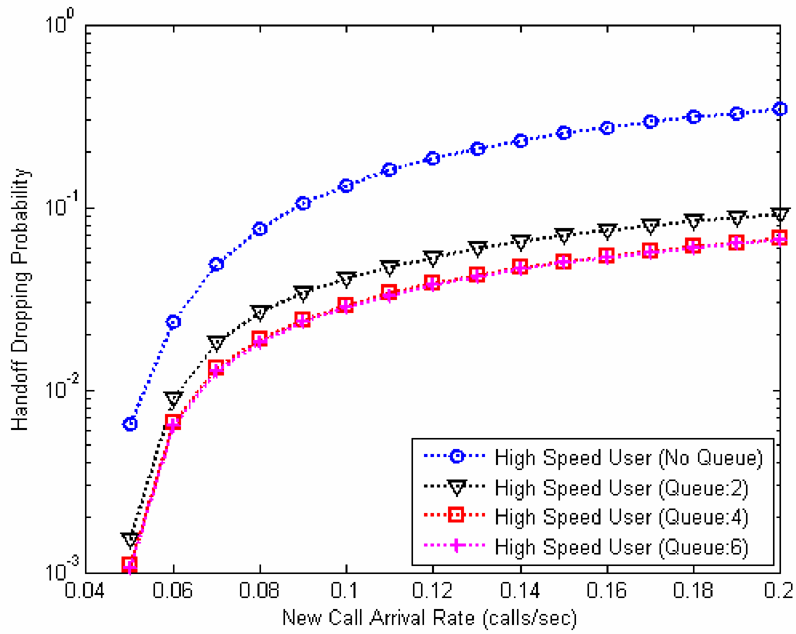

Figure 4.7 Handoff dropping probability for high speed users with different queue sizes.

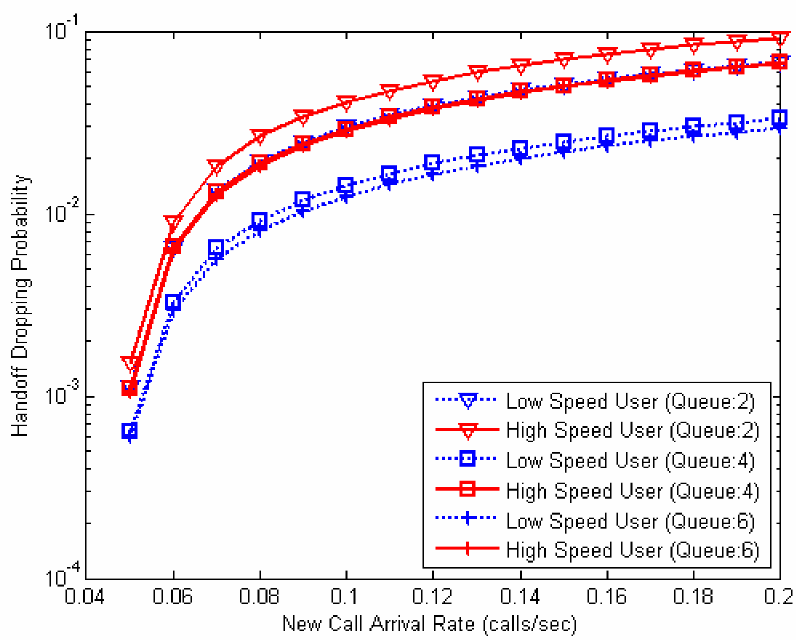

Figure 4.8 Comparison of handoff dropping probabilities for low and high speed users with different queue sizes.

4.5 NUMERICAL RESULTS FOR TWO-TIER CELLULAR NETWORK WITH A FIFO QUEUE IN THE MACROCELL UTILIZED BY TWO TYPES OF USERS

In this section, the results obtained for a two-tier network with a FIFO queue in the macrocell utilized by two types of users are presented. The queue is in the macrocell and shared by high speed users and overflowed low speed users.

The new call blocking probability for low speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users is illustrated in Figure 4.9. From this figure, it can be observed that the queue size has a very slight effect on the new call blocking probability. This is due to the fact that the handoff calls have higher priorities than the new calls in acquiring the free channels.

The handoff call blocking probability for low speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users is shown in Figure 4.10. This figure shows that as the queue size increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and queue size.

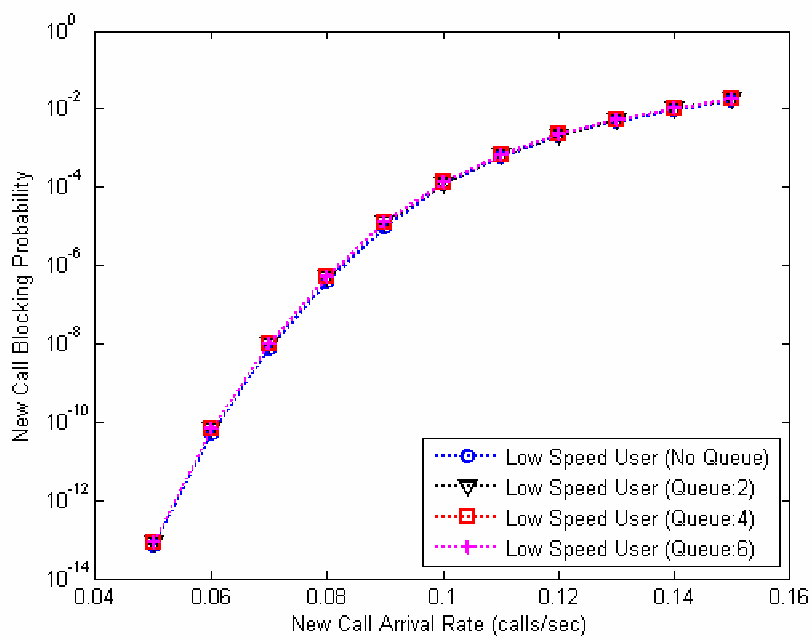

Figure 4.9 New call blocking probability of low speed users with different queue sizes.

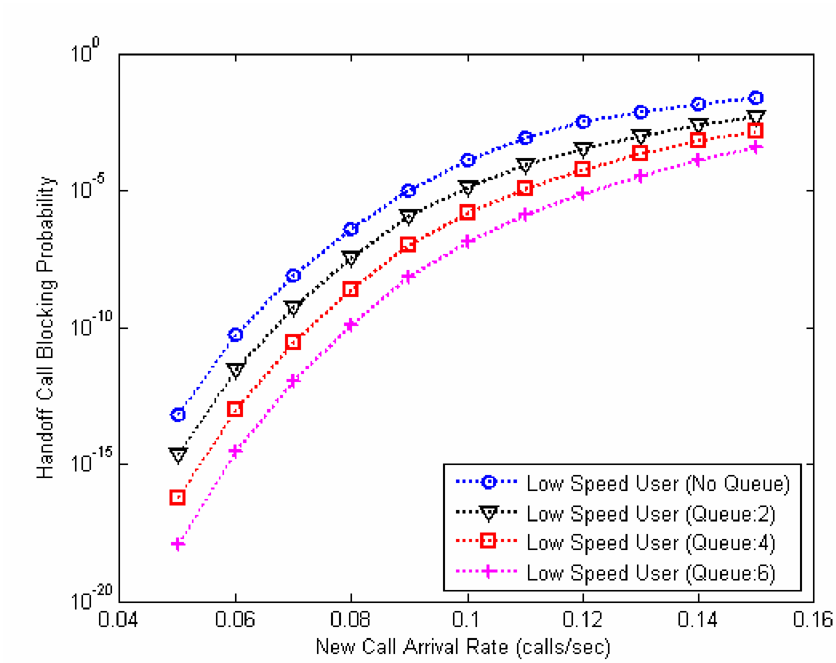

Figure 4.10 Handoff call blocking probability of low speed users with different queue sizes.

Figure 4.11 represents the handoff dropping probability for low speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users. The handoff dropping probability decreases significantly up to a queue size of 4. However, as queue size increases beyond 4, the handoff dropping probability decreases very slightly.

The new call blocking probability for high speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users is shown in Figure 4.12. From this figure, it can be observed that the queue size has a very slight effect on the new call blocking probability. This is due to the fact that the handoff calls have higher priorities than the new calls in acquiring the free channels.

The handoff call blocking probability for high speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users is illustrated in Figure 4.13. This figure shows that, as the queue size increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and queue size. As the queue size increases, the handoff call blocking probability decreases.

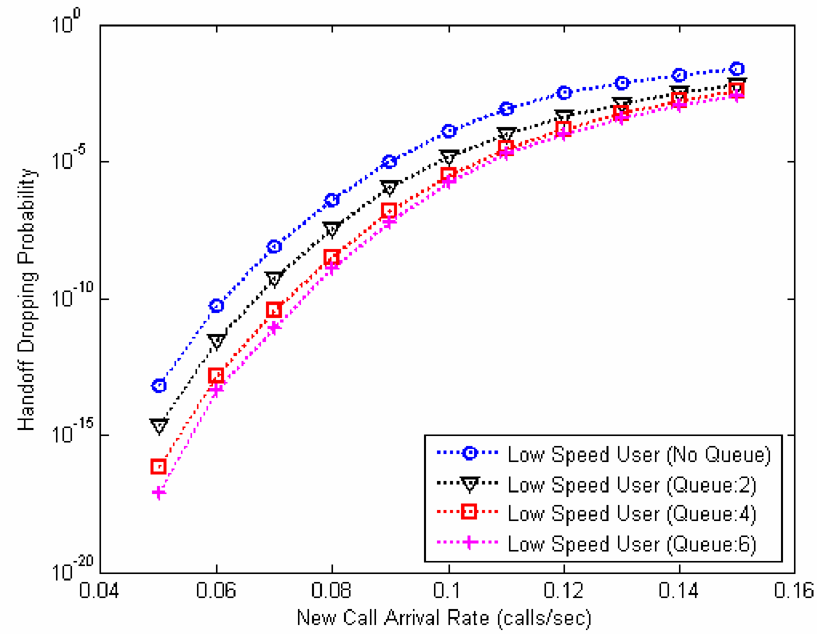

Figure 4.11 Handoff dropping probability of low speed users with different queue sizes.

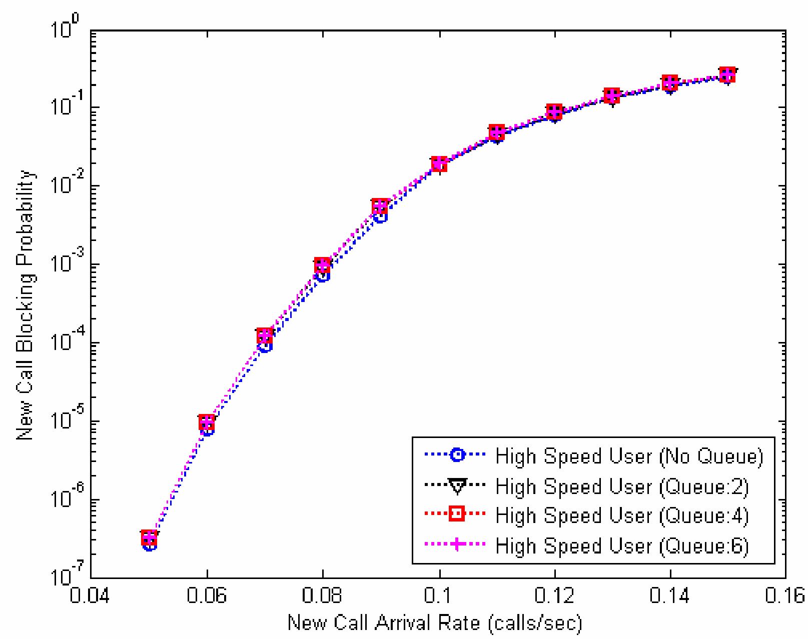

Figure 4.12 New call blocking probability of high speed users with different queue sizes.

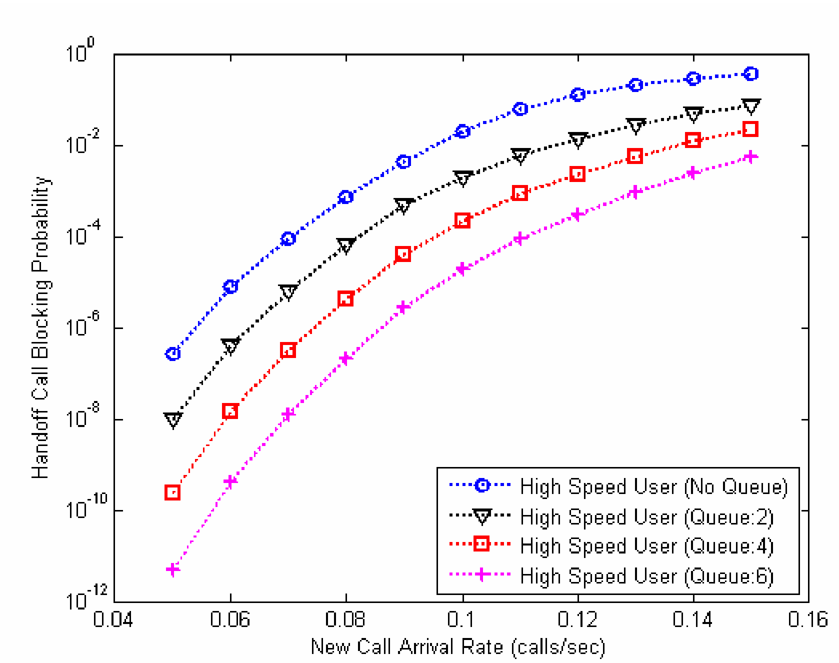

Figure 4.13 Handoff call blocking probability of high speed users with different queue sizes.

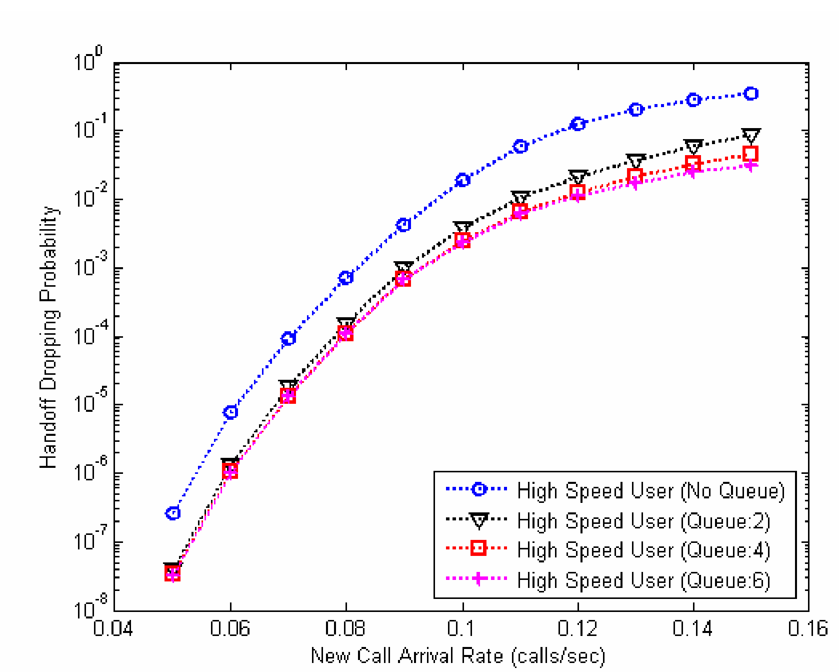

Figure 4.14 Handoff dropping probability of high speed users with different queue sizes.

Figure 4.14 shows the handoff dropping probability for high speed users in a two-tier cellular network with a FIFO queue in the macrocell utilized by two types of users. The handoff dropping probability decreases significantly up to a queue size of 4. However, as queue size increases beyond 4, the handoff dropping probability decreases very slightly.

The comparison of the new call blocking probability for low and high speed users is shown in Figure 4.15. The new call blocking probability of low speed users is lower than corresponding high speed users' new call blocking probability. This property results from the overflow effect of low speed users which is not available for high speed users. The overflow effect enables a low speed user to use more channels than a high speed user.

Figure 4.16 shows the comparison of the handoff call blocking probability for low and high speed users. The handoff call blocking probability of low speed users is lower than corresponding high speed users' handoff call blocking probability. This results from the effect that low speed users are able to use the channels in the macrocell also where high speed users use the macrocell channels only.

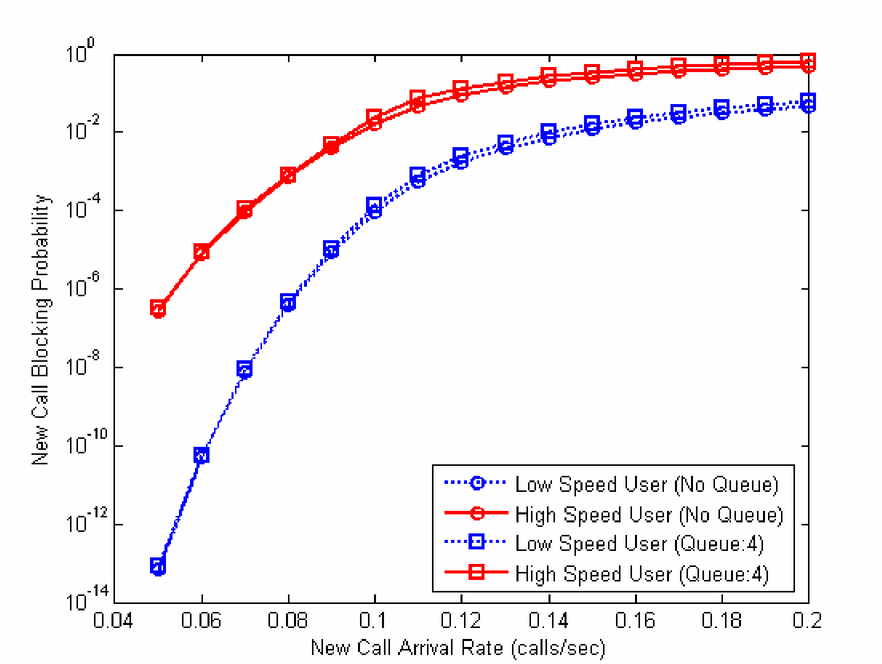

Figure 4.15 Comparison of new call blocking probabilities for low and high speed users with different queue sizes.

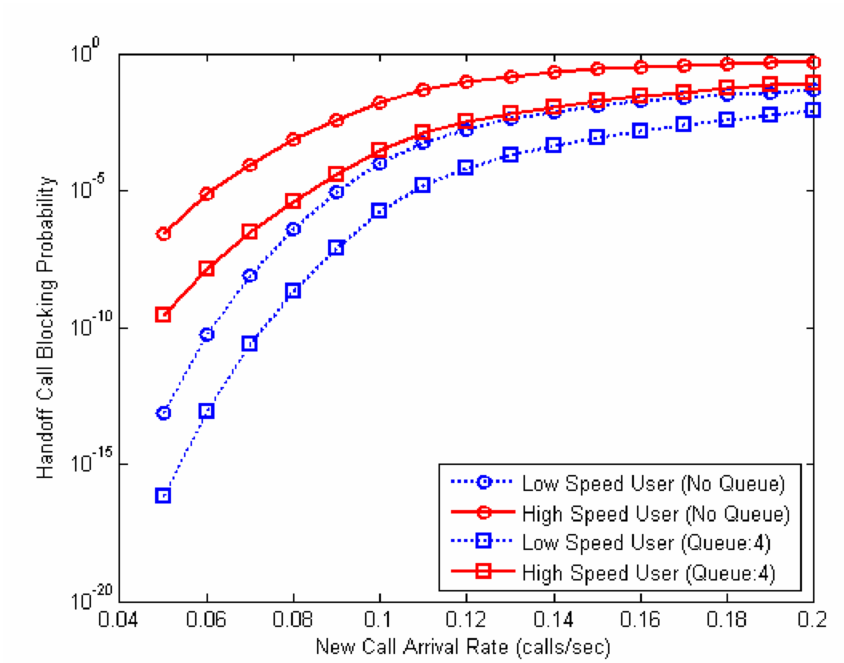

Figure 4.16 Comparison of handoff call blocking probabilities for low and high speed users with different queue sizes.

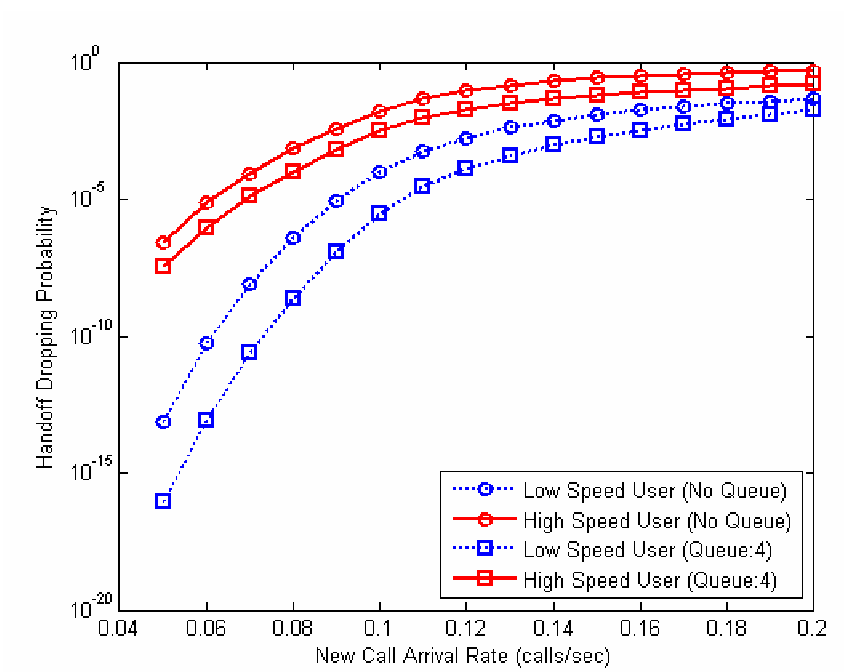

Figure 4.17 Comparison of handoff dropping probabilities for low and high speed users with different queue sizes.

The comparison of the handoff dropping probability for low and high speed users is presented in Figure 4.17. The handoff dropping probability of low speed users is lower than corresponding high speed users' handoff call blocking probability. This property again results from the overflow effect of low speed users which is not available for high speed users.

4.6 NUMERICAL RESULTS FOR TWO-TIER CELLULAR NETWORK WITH A FIFO QUEUE IN THE MICROCELL UTILIZED BY TWO TYPES OF USERS

In this section, the results obtained for a two-tier network with a FIFO queue in the microcell utilized by two types of users are presented. The queue is in the microcell and used only by low speed users.

The new call blocking probability for low speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users is illustrated in Figure 4.18. From this figure it can be observed that the queue size has a very slight effect on the new call blocking probability.

Figure 4.19 shows the handoff call blocking probability for low speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users. This figure shows that as the queue size increases, the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and queue size.

Figure 4.20 represents the handoff dropping probability for low speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users. The handoff dropping probability decreases significantly up to a queue size of 2. However, as queue size increases beyond 2, the handoff dropping probability decreases very slightly.

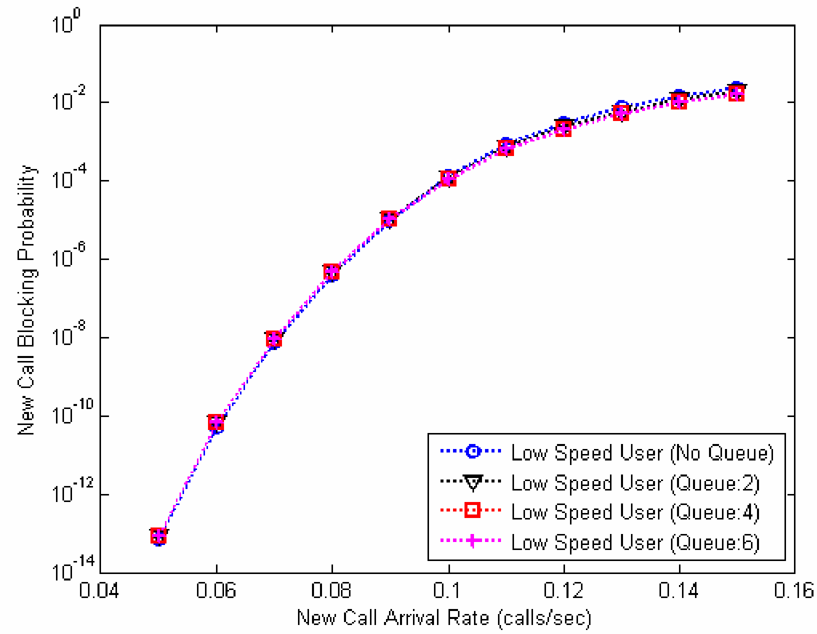

Figure 4.18 New call blocking probability of low speed users with different queue sizes.

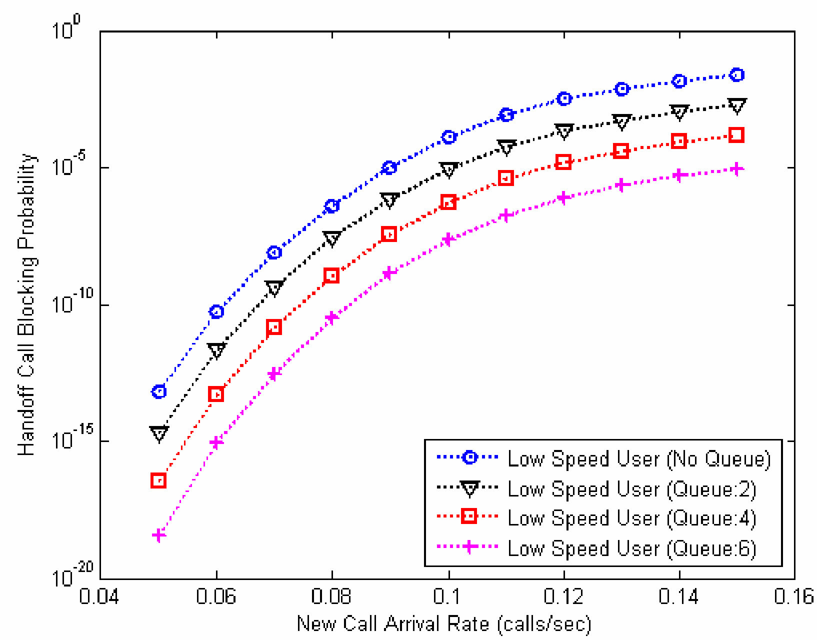

Figure 4.19 Handoff call blocking probability of low speed users with different queue sizes.

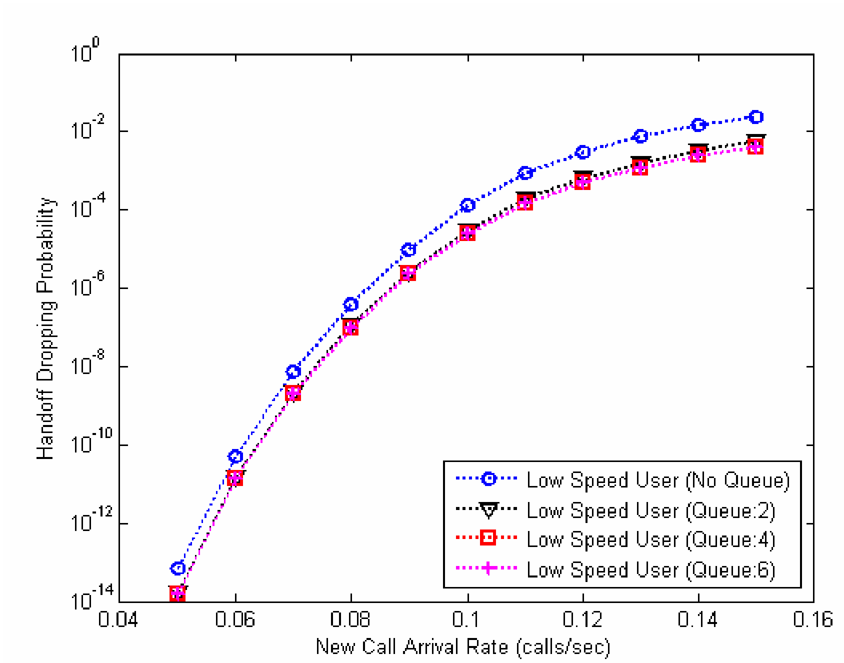

Figure 4.20 Handoff dropping probability of low speed users with different queue sizes.

The new call blocking probability for high speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users can be observed in Figure 4.21. The new call blocking probability decreases when the queue size increases in the microcell. The effect is due to the handoff arrival rate for overflowed low speed handoff calls to the macrocell. When the queue size increases the overflow rates decreases, hence the new calls of the macrocell acquire more channels.

The handoff call blocking probability for high speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users is shown in Figure 4.22. This figure shows that, as the queue size increases the handoff call blocking probability decreases. The decreasing effect is similar to the new call blocking probability results in Figure 4.21.

Figure 4.23 shows the handoff dropping probability for high speed users in a two-tier cellular network with a FIFO queue in the microcell utilized by two types of users. The handoff dropping probability is same as the handoff call blocking probability for high speed users since there is no queue in the macrocell layer.

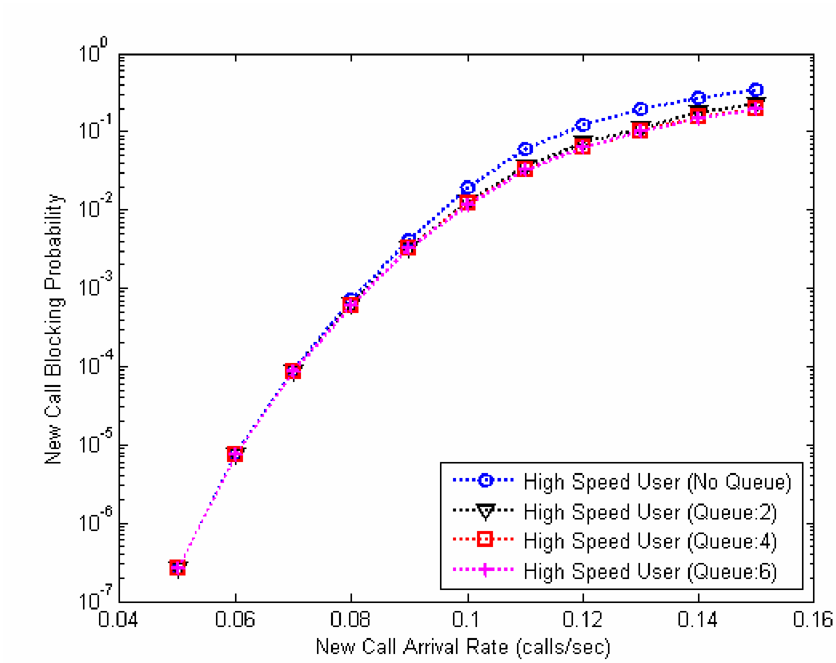

Figure 4.21 New call blocking probability of high speed users with different queue sizes.

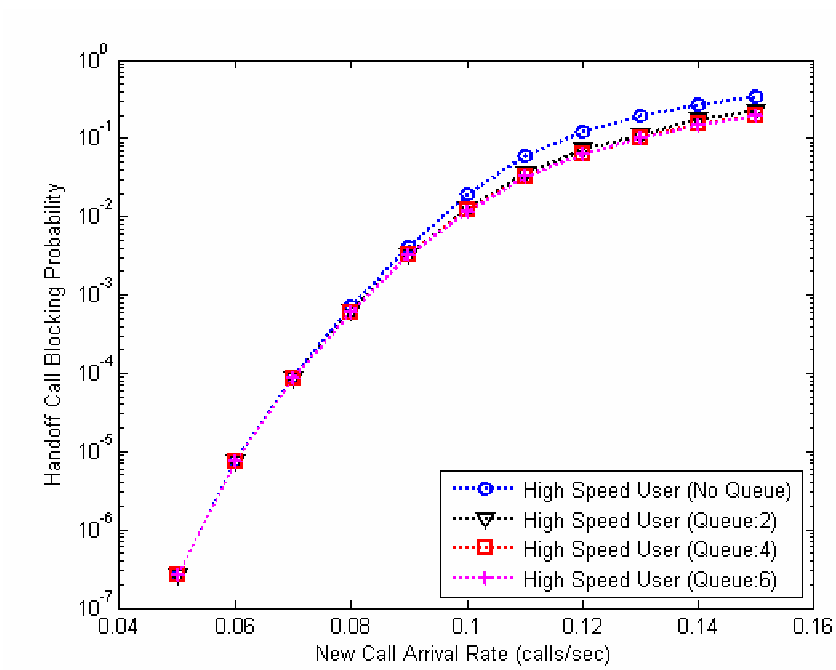

Figure 4.22 Handoff call blocking probability of high speed users with different queue sizes.

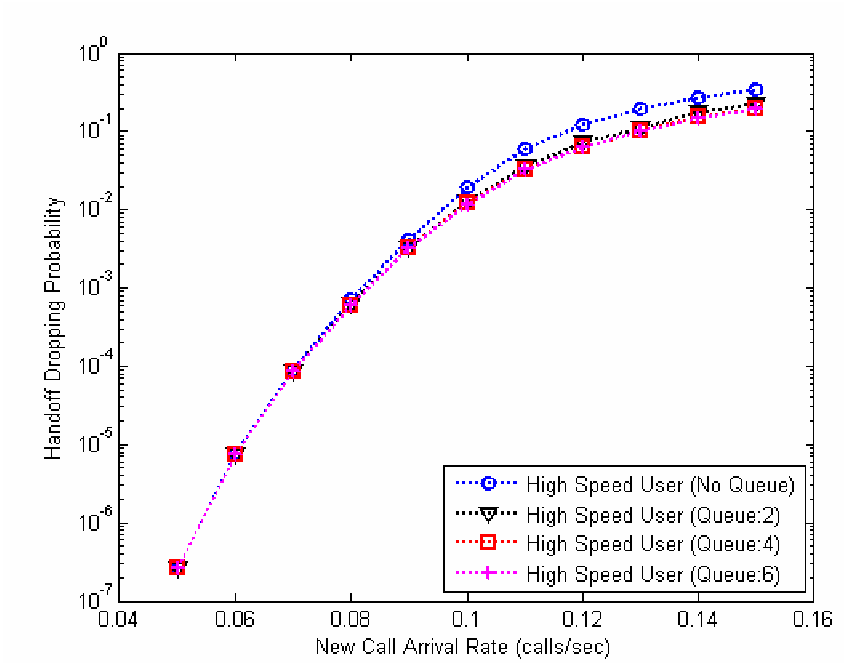

Figure 4.23 Handoff dropping probability of high speed users with different queue sizes.

The comparison of the new call blocking probability for low and high speed users is shown in Figure 4.24. The new call blocking probability of low speed users is lower than corresponding high speed users' new call blocking probability. This property results from the overflow effect of low speed users which is not available for high speed users. The overflow effect enables a low speed user to use more channels than a high speed user.

The comparison of the handoff call blocking probability for low and high speed users can be observed in Figure 4.25. The handoff call blocking probability of low speed users is lower than corresponding high speed users' handoff call blocking probability. This property again results from the overflow effect of new call blocking probability for low speed users.

Figure 4.26 illustrates the comparison of the handoff dropping probability for low and high speed users. The handoff dropping probability of low speed users is better than corresponding high speed users' handoff call blocking probability.

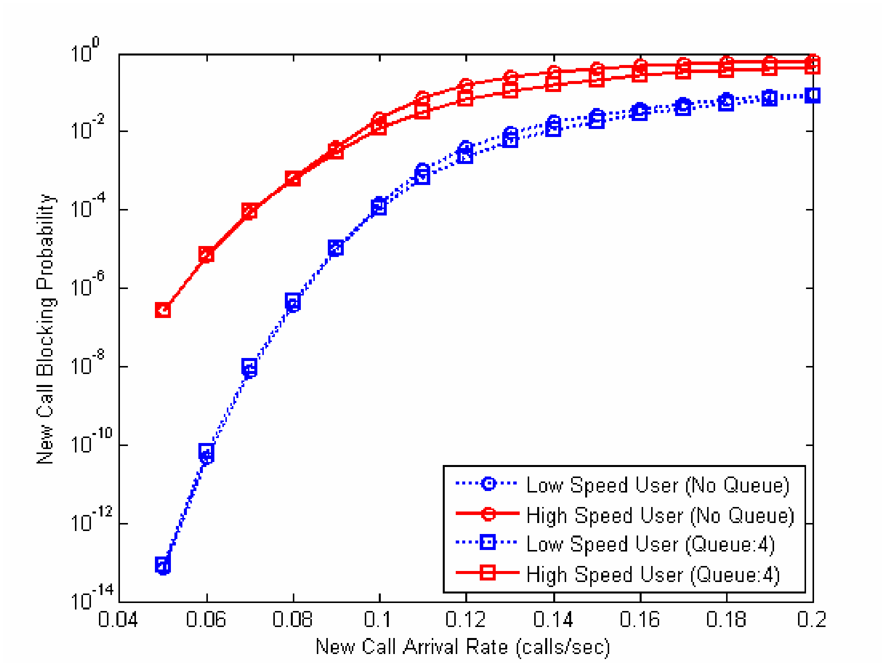

Figure 4.24 Comparison of new call blocking probabilities for low and high speed users with different queue sizes.

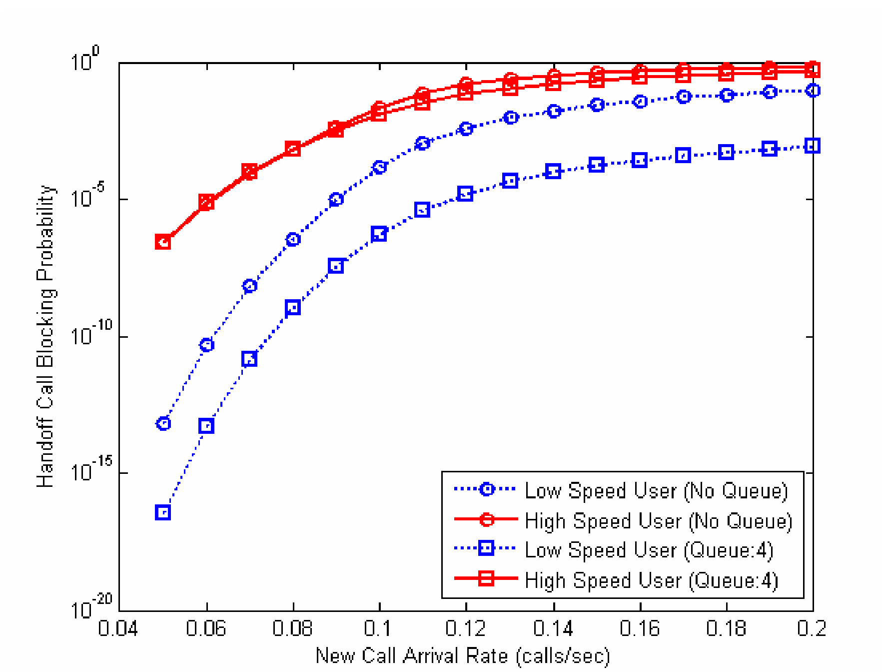

Figure 4.25 Comparison of handoff call blocking probabilities for low and high speed users with different queue sizes.

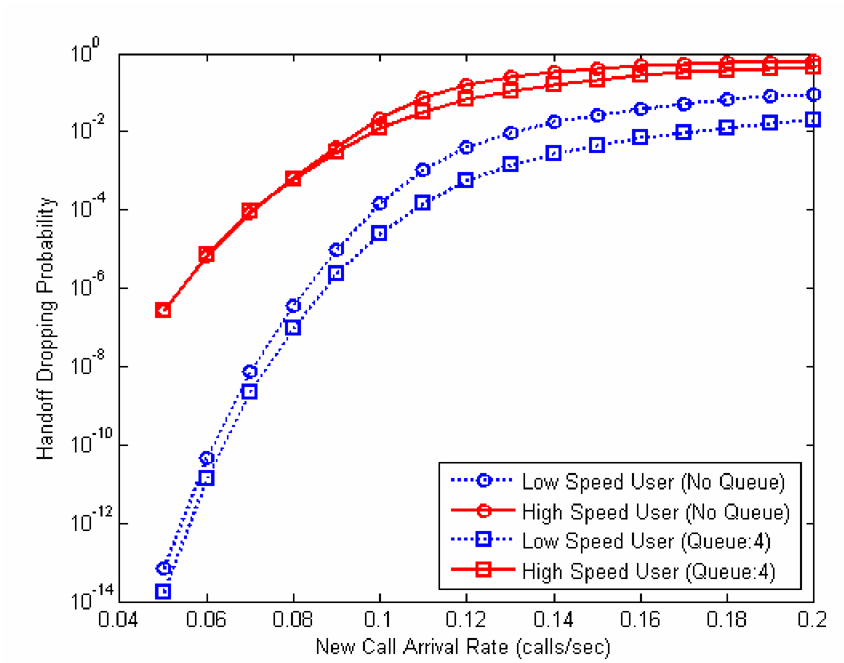

Figure 4.26 Comparison of handoff dropping probabilities for low and high speed users with different queue sizes.

4.7 NUMERICAL RESULTS FOR TWO-TIER CELLULAR NETWORK WITH GUARD CHANNELS IN MACROCELL UTILIZED BY TWO TYPES OF USERS

In this section, the results obtained for a two-tier network with guard channels in the macrocell utilized by two types of users are presented. The guard channels are in the macrocell and shared by high speed users and overflowed low speed users.

The new call blocking probability for low speed users in a two-tier cellular network with guard channels in the macrocell utilized by two types of users is shown in Fig. 4.27. The new call blocking probability of low speed users decreases slightly with an increase in the number of guard channels. This is due to the fact that an increase in guard channel size implies an increase in overall channel capacity.

The handoff call blocking probability for low speed users in a two-tier cellular network with guard channels in the macrocell utilized by two types of users is presented in Fig. 4.28. This figure shows that as the number of guard channels increases the handoff call blocking probability decreases. The handoff call blocking probability decreases as extra guard channels are presented to the network.

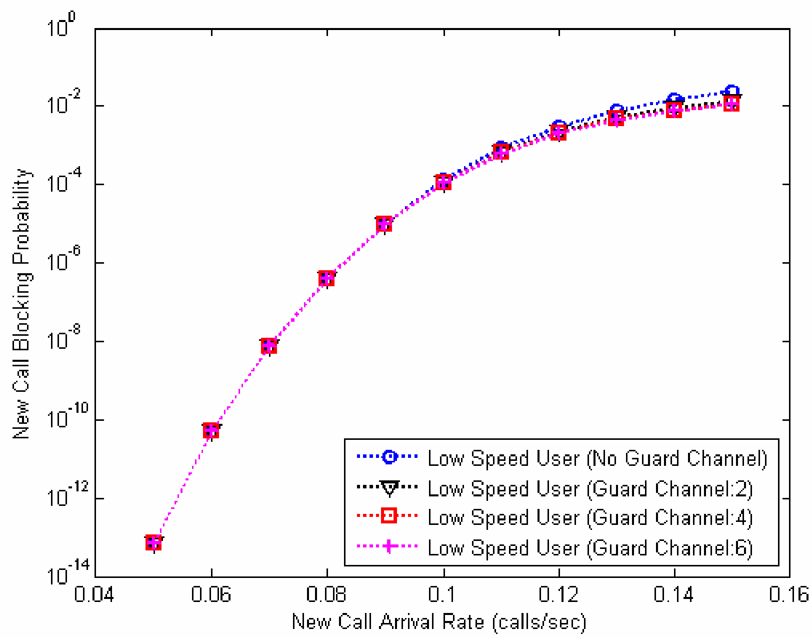

Figure 4.27 New call blocking probability of low speed users with guard channels.

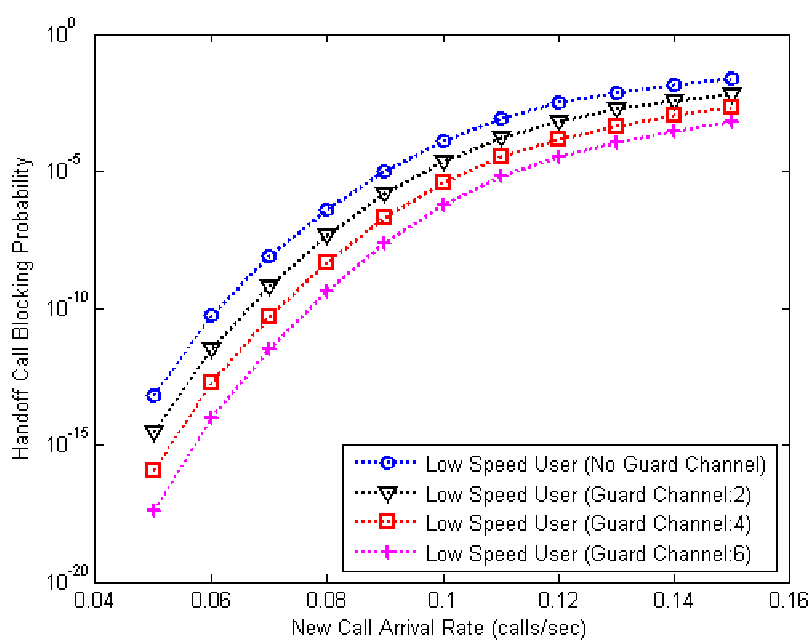

Figure 4.28 Handoff call blocking probability of low speed users with different guard channel sizes.

The new call blocking probability for high speed users in a two-tier cellular network with guard channels in the macrocell utilized by two types of users is shown in Figure 4.29. The new call blocking probability of low speed users decreases slightly with an increase in the number of guard channels. This is due to the fact that an increase in guard channel size implies an increase in overall channel capacity.

Figure 4.30 shows the handoff call blocking probability for high speed users in a two-tier cellular network with guard channels in the macrocell utilized by two types of users. This figure shows that, as the number of guard channels increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and number of guard channels.

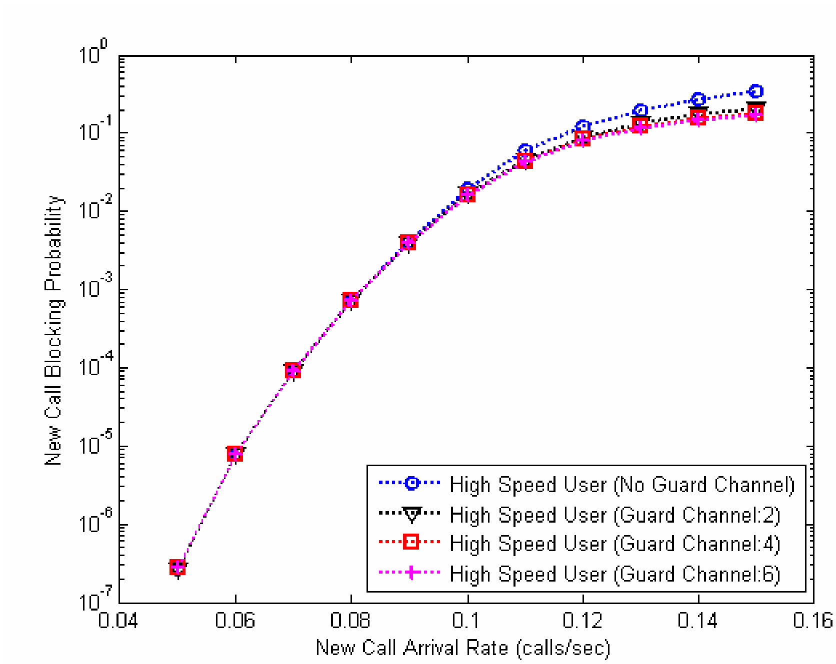

Figure 4.29 New call blocking probability of high speed users with different guard channel size.

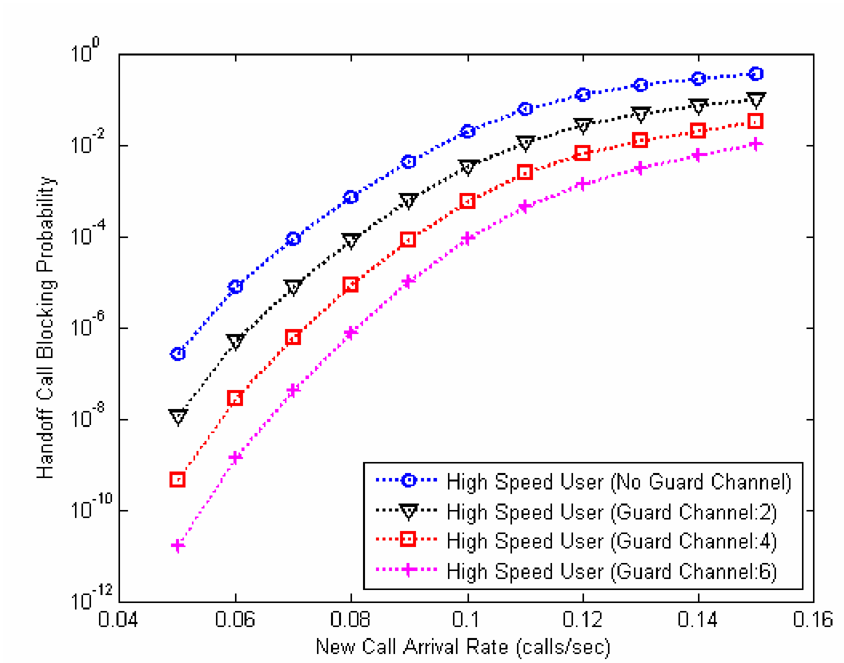

Figure 4.30 Handoff call blocking probability of high speed users with different guard channel size.

The comparison of the new call blocking probability for low and high speed users can be observed in Figure 4.31. The new call blocking probability of low speed users is lower than corresponding high speed users' new call blocking probability. This property results from the overflow effect of low speed users which is not available for high speed users. The overflow effect enables a low speed user to use more channels than a high speed user.

The comparison of the handoff call blocking probability for low and high speed users is presented in Figure 4.32. The handoff call blocking probability of low speed users is lower than corresponding high speed users' handoff call blocking probability. Handoff calls of low speed users benefit from both the microcells' and macrocells' channels in contrast to high speed one that can use only the macrocells' channels.

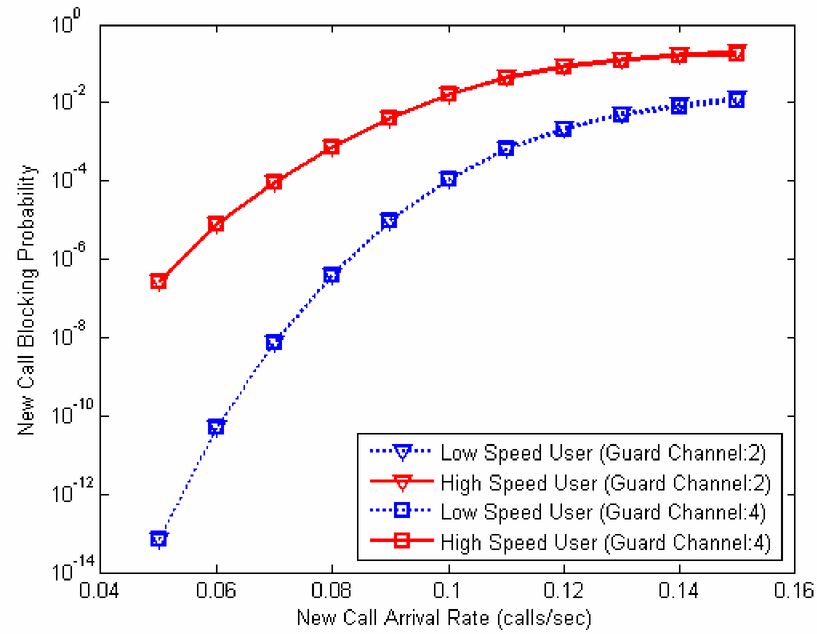

Figure 4.31 Comparison of new call blocking probabilities for low and high speed users with different guard channel sizes.

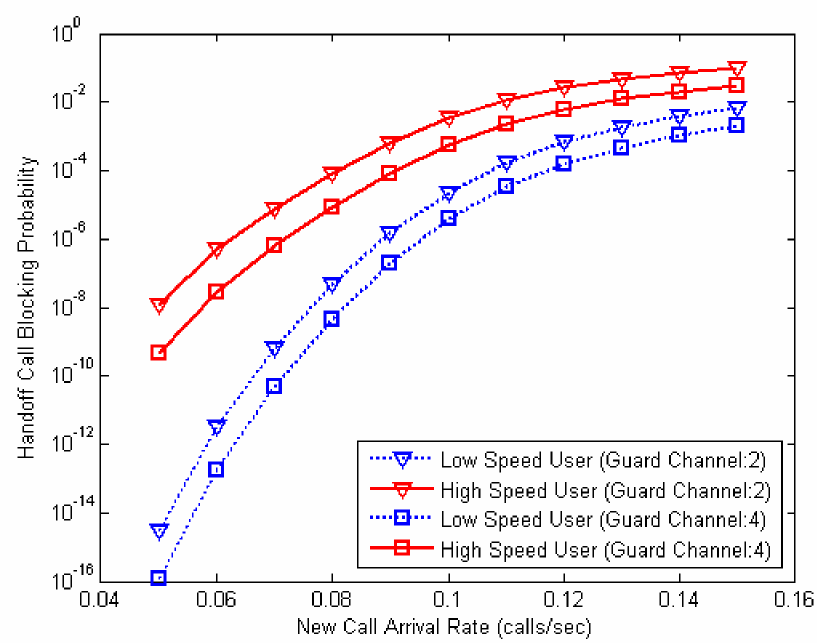

Figure 4.32 Comparison of handoff call blocking probabilities for low and high speed users with different guard channel sizes.

4.8 NUMERICAL RESULTS FOR TWO-TIER CELLULAR NETWORK WITH GUARD CHANNELS IN THE MICROCELL UTILIZED BY TWO TYPES OF USERS

In this section, the results obtained for a two-tier network with guard channels in the microcell utilized by two types of users are presented. The guard channels are in the microcell and used only by low speed users.

The new call blocking probability for low speed users in a two-tier cellular network with guard channels in the microcell utilized by two types of users is shown in Figure 4.33. From this figure, it can be observed that the queue size has a very slight effect on the new call blocking probability.

The handoff call blocking probability for low speed users in a two-tier cellular network with guard channels in the microcell utilized by two types of users can be observed in Figure 4.34. This figure shows that, as the number of guard channels increases the handoff call blocking probability decreases. The decreasing effect is a result of indirect proportionality between handoff call blocking probability and the number of guard channels.

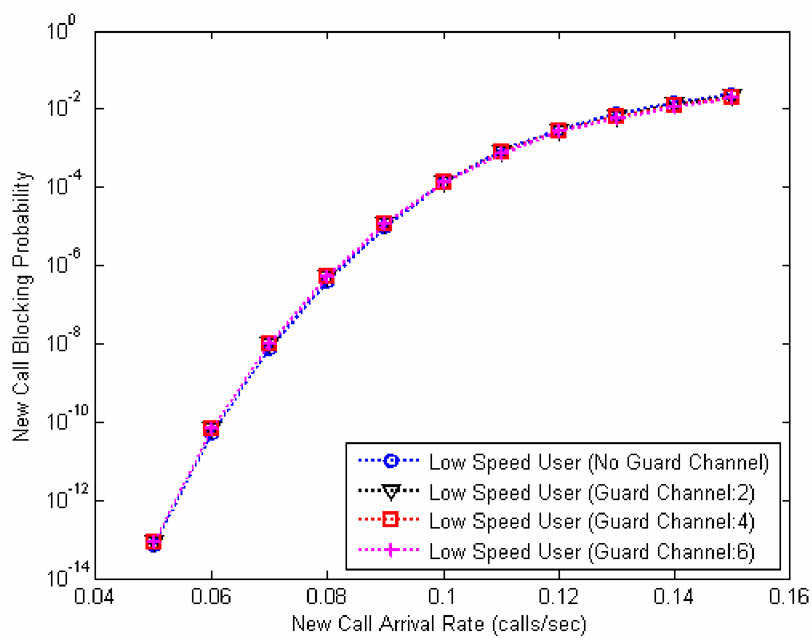

Figure 4.33 New call blocking probability of low speed users with guard channels.

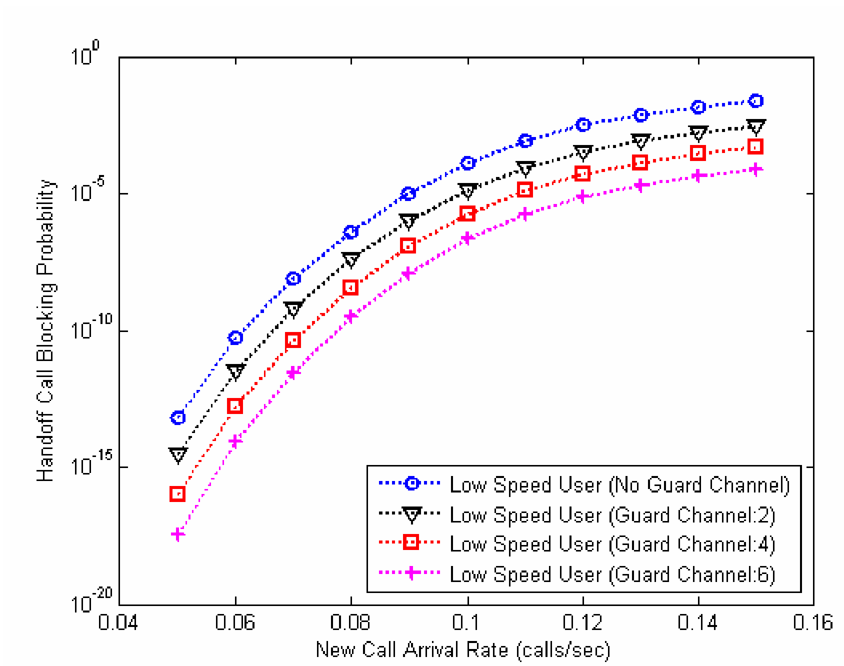

Figure 4.34 Handoff call blocking probability of low speed users with different guard channel sizes.

The new call blocking probability for high speed users in a two-tier cellular network with guard channels in the microcell utilized by two types of users is presented in Figure 4.35. The new call blocking probability decreases when the number of guard channels increases in the microcell. The effect is due to the handoff arrival rate for overflowed low speed handoff calls to the macrocell. When the number of guard channels is larger, the overflow rates become lower, hence the new calls of the macrocell acquire more channels.

Figure 4.36 illustrates the handoff call blocking probability for high speed users in a two-tier cellular network with guard channels in the microcell utilized by two types of users. The handoff blocking probability is the same as the new call blocking probability for high speed users because no guard channels are presented in the macrocell.

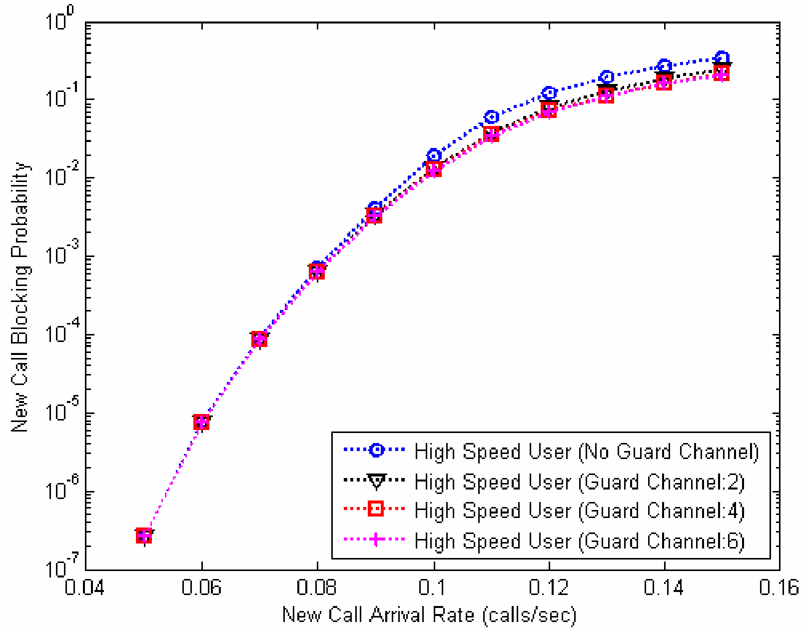

Figure 4.35 New call blocking probability of high speed users with different guard channel sizes.

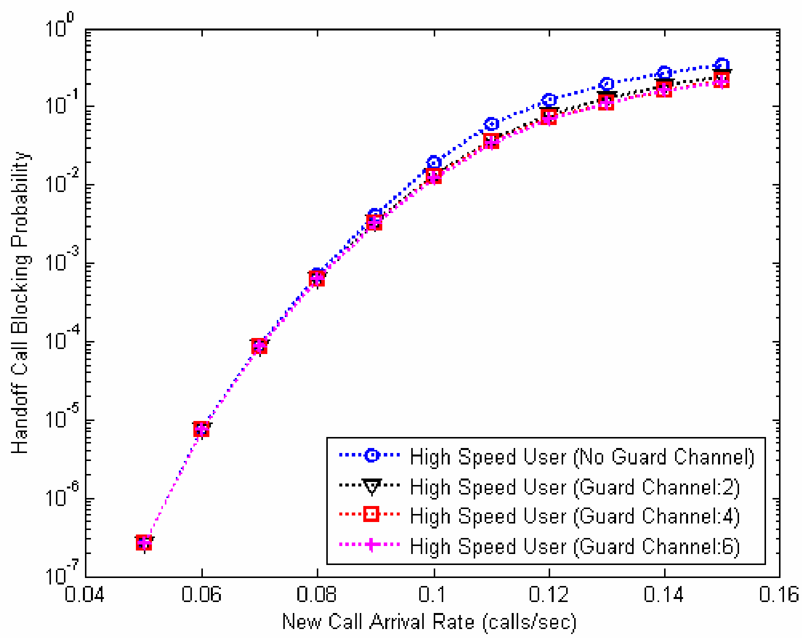

Figure 4.36 Handoff call blocking probability of high speed users with different guard channel sizes.

The comparison of the new call blocking probability for low and high speed users is shown in Figure 4.37. The new call blocking probability of low speed users is lower than corresponding high speed users' new call blocking probability. This property results from the overflow effect of low speed users which is not available for high speed users.

The comparison of the handoff call blocking probability for low and high speed users is shown in Figure 4.38. The handoff call blocking probability of low speed users is lower than corresponding high speed users' handoff call blocking probability. This property again results from the overflow effect of low speed users.

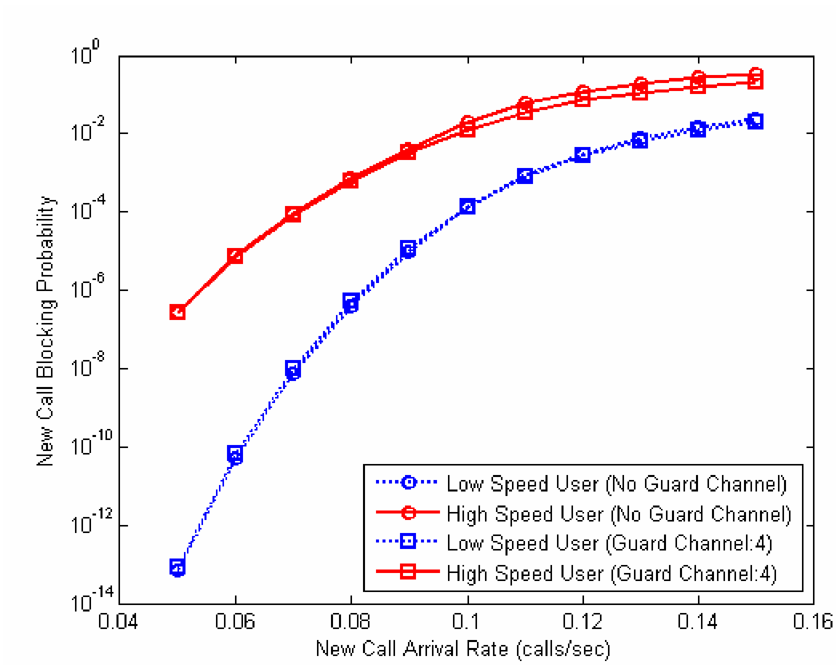

Figure 4.37 Comparison of new call blocking probabilities for low and high speed users with different guard channel sizes.

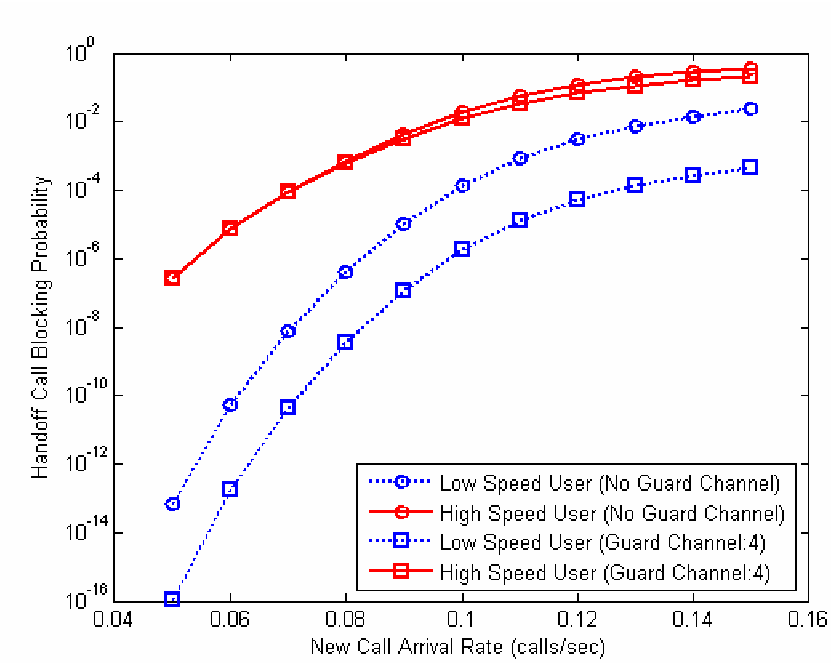

Figure 4.38 Comparison of handoff call blocking probabilities for low and high speed users with different guard channel sizes.

4.9 NUMERICAL RESULTS FOR COMPARISON OF TWO-TIER NETWORKS WITH FIFO QUEUE IN MICROCELL / MACROCELL

In this section, the results obtained for a two-tier network with a FIFO queue in both the microcell and the macrocell utilized by two user types are compared.

The comparison of the new call blocking probability for low speed users is shown in Fig. 4.39. The existence of a queue in the microcell or macrocell has similar effect on the new call blocking probability.

The comparison of the handoff call blocking probability for low speed users can be observed in Fig. 4.40. The handoff blocking probability for low speed users with FIFO queue in the microcell is lower than the handoff blocking probability with queue in the macrocell. This result can be explained as follows: The existence of a queue in the microcell can be utilized only by low speed users. However, the existence of a queue in the macrocell can be utilized by both low and high speed users.

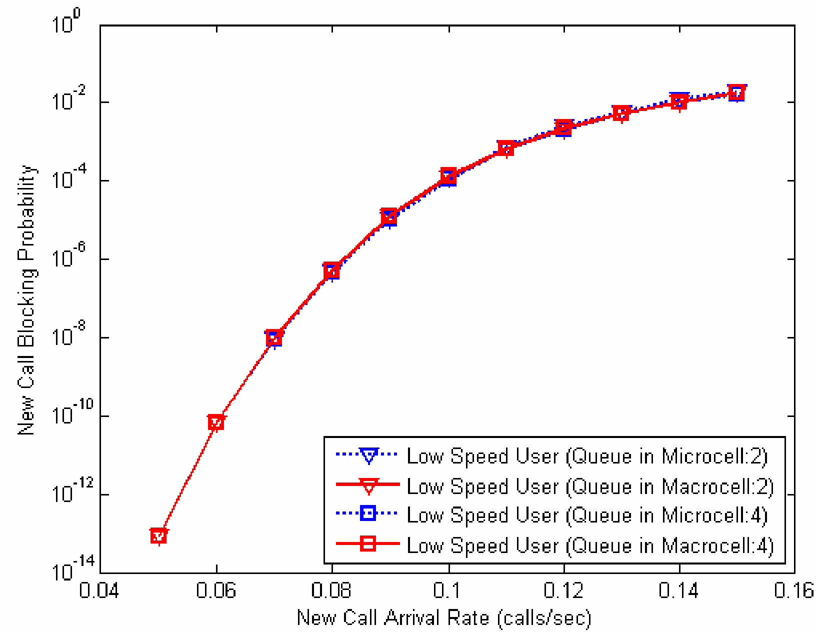

Figure 4.39 Comparison of new call blocking probabilities for low speed users with different queue sizes.

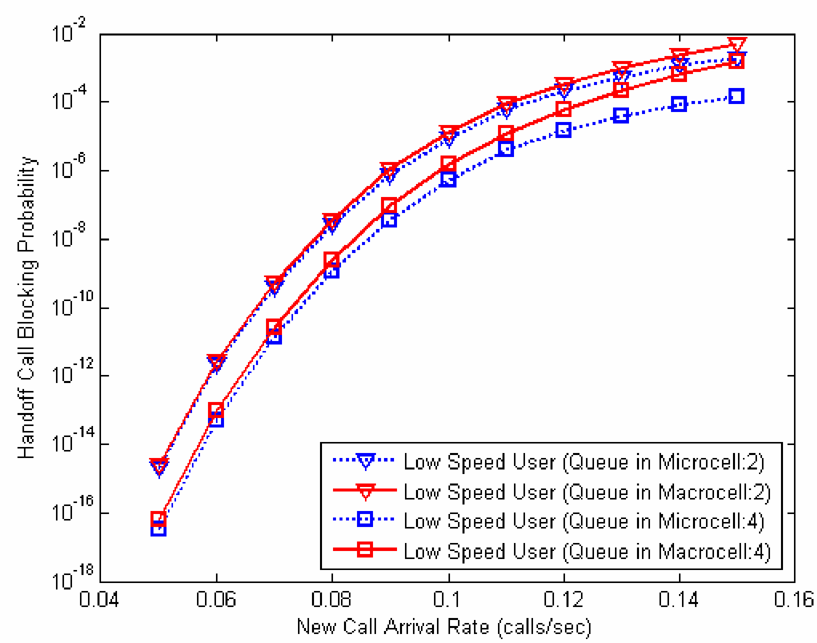

Figure 4.40 Comparison of handoff call blocking probabilities for low speed users with different queue sizes.

The comparison of the handoff dropping probability for low speed users is shown in Figure 4.41. The handoff dropping probability for low speed users in a network with a queue in the macrocell is lower than a network with a queue in the microcell. A lower handoff dropping probability in the macrocell results from the fact that a low speed user has more chance to stay in a queue in the macrocell because the macrocell covers much larger area than the microcell.

Figure 4.42 represents the comparison of the new call blocking probability for high speed users. The new call blocking probability for high speed users in a network with a queue in the microcell is lower than the new call blocking probability in a network with a queue in the macrocell. The argument for this result is as follows: The existence of a queue in the microcell allows the system to handle more handoff calls of low speed users. This results in a lower overflow rate for handoff calls in the microcell than the macrocell.

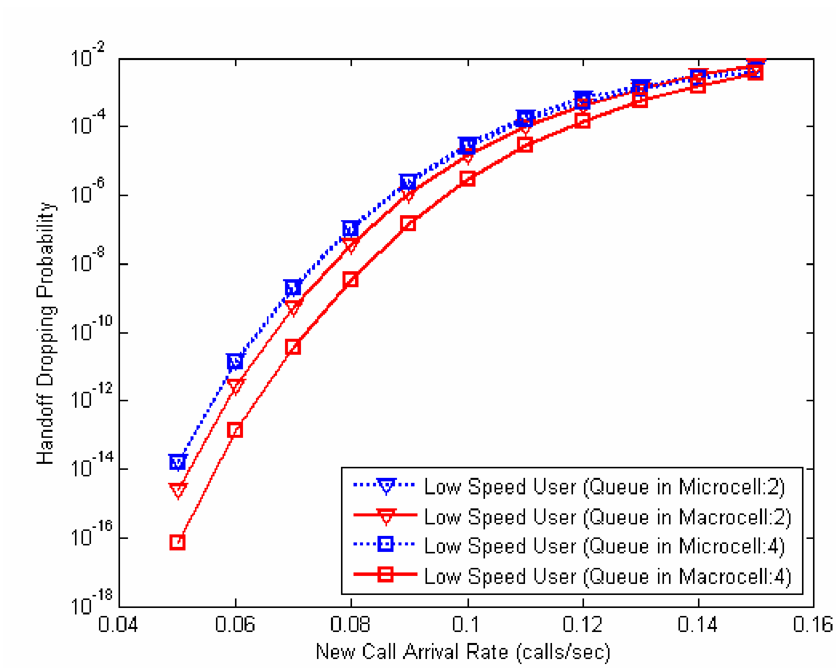

Figure 4.41 Comparison of handoff dropping probabilities for low speed users with different queue sizes.

The comparison of the handoff call blocking probability for high speed users is shown in Figure 4.43. The handoff blocking probability of high speed users in a network with a queue in the microcell does not change much with respect to an increase in the queue size. However, the handoff blocking probability for high speed users of a network with a queue in the macrocell decreases with an increase in the queue size. In all cases, the handoff blocking probability for high speed users in a network with a queue in the macrocell is lower than the case where the queue is in the microcell.

The comparison of the handoff dropping probability for high speed users is illustrated in Figure 4.44. The handoff dropping probability of high speed users in a network with a queue in the microcell is higher than the case where the queue is in the macrocell. In addition, the queue size does not have a significant effect on the handoff dropping probability. As we discussed earlier for the case of handoff blocking probability, the handoff dropping probability is also lower for a network with queue in the microcell than the case of a microcell. The handoff dropping probability of a cellular network for high speed users with a queue in the macrocell slightly decreases as the queue size increases.

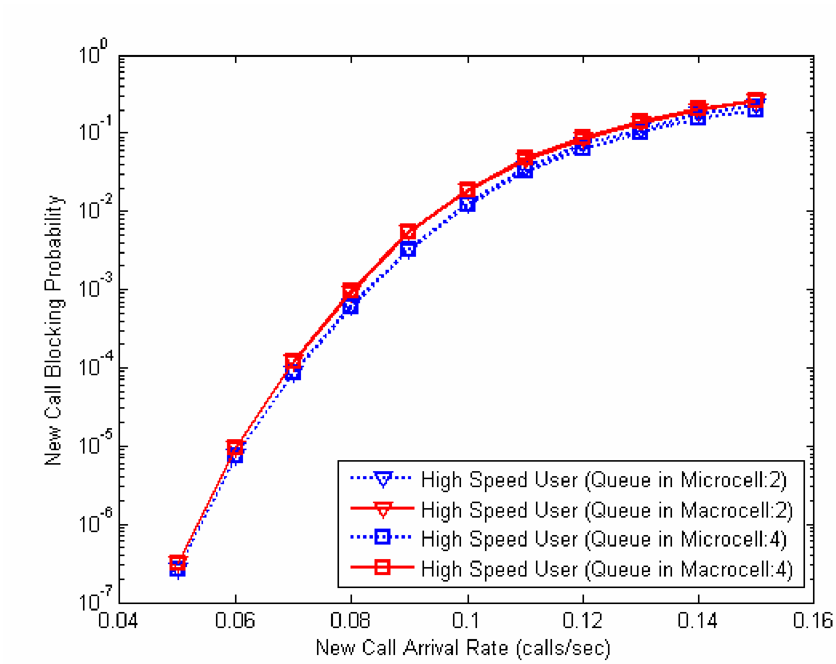

Figure 4.42 Comparison of new call blocking probabilities for high speed users with different queue sizes.

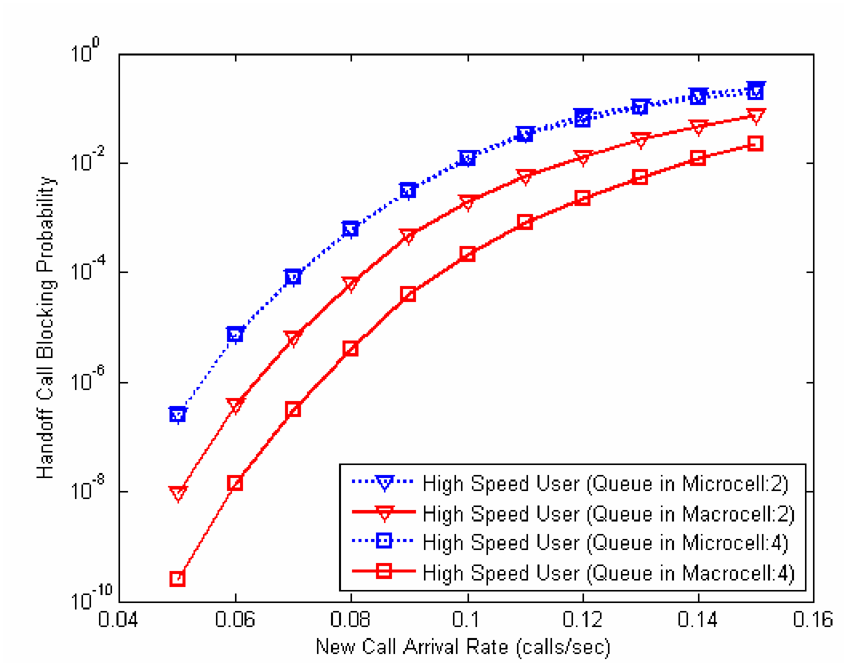

Figure 4.43 Comparison of handoff call blocking probabilities for high speed users with different queue size.

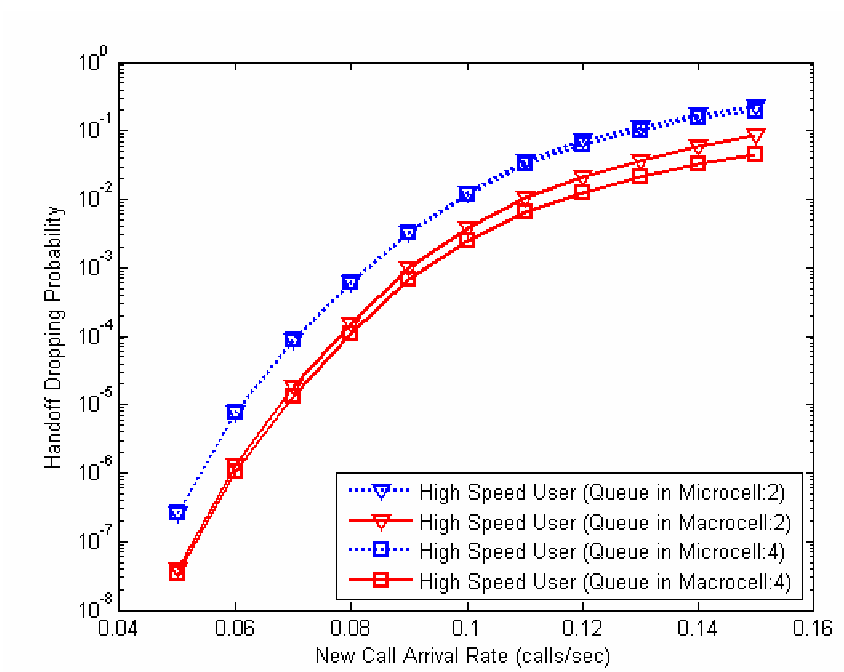

Figure 4.44 Comparison of handoff dropping probabilities for high speed users with different queue sizes.

4.10 NUMERICAL RESULTS FOR COMPARISON OF TWO-TIER NETWORKS WITH FIFO QUEUE AND GUARD CHANNELS IN MACROCELL

In this section, the results obtained for a two-tier network with a FIFO queue in the macrocell and a two-tier network with guard channels in the macrocell utilized by two user types are compared.

The comparison of the new call blocking probability for low speed users is shown in Figure 4.45. The existence of a queue or guard channels in the macrocell has similar effect on the new call blocking probability of low speed users.

Fig. 4.46 shows the comparison of the handoff call blocking probability for low speed users. A network with a queue has lower handoff call blocking probability than a network with guard channels in the macrocell for low speed users. Also, as the queue or guard channel size increases the handoff call blocking probability decreases.

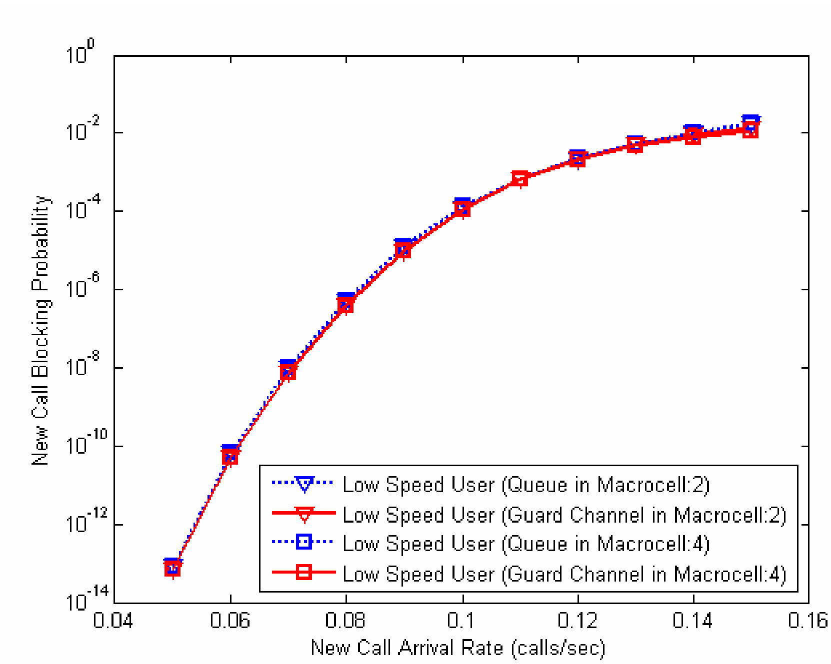

Figure 4.45 Comparison of new call blocking probabilities for low speed users with different queue and guard channel sizes.

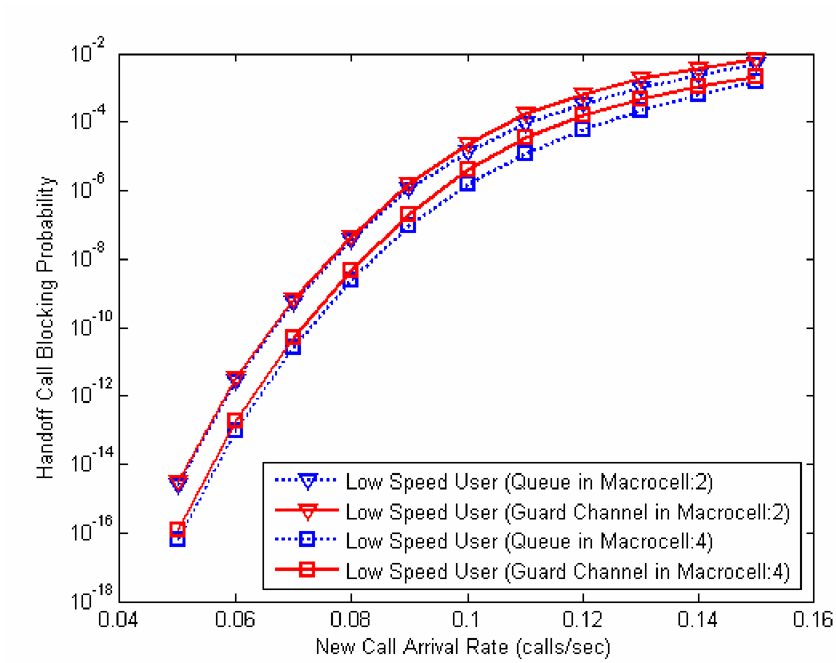

Figure 4.46 Comparison of handoff call blocking probabilities for low speed users with different queue and guard channel sizes.

The comparison of the new call blocking probability for high speed users is presented in Figure 4.47. The existence of a queue or guard channels in the macrocell has similar effect on the new call blocking probability of low speed users.

The comparison of the handoff call blocking probability for high speed users can be observed in Figure 4.48. A network with a queue has lower handoff call blocking probability than a network with guard channels in the macrocell for high speed users. Also, as the queue or guard channels size increases, the handoff call blocking probability decreases.

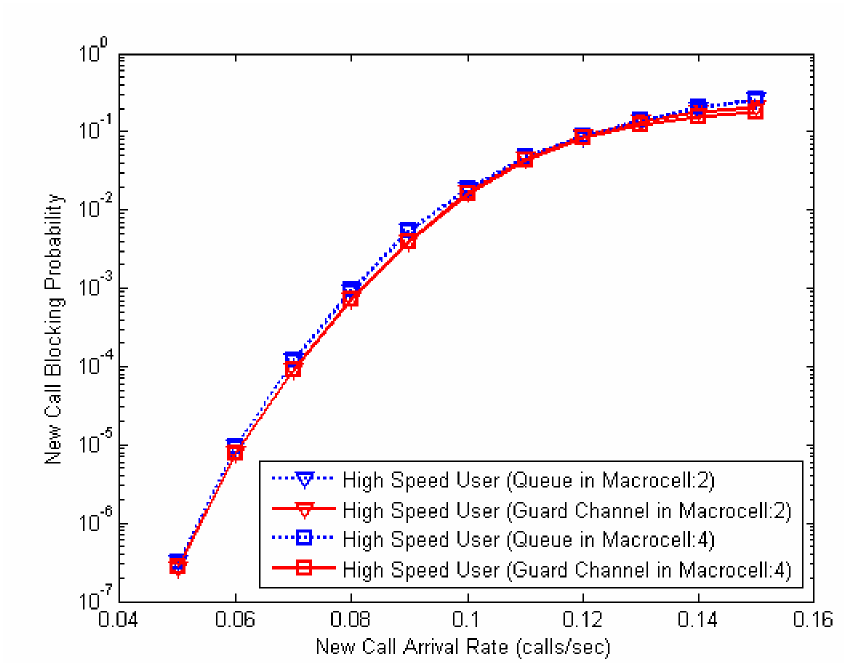

Figure 4.47 Comparison of new call blocking probabilities for high speed users with different queue and guard channel sizes.

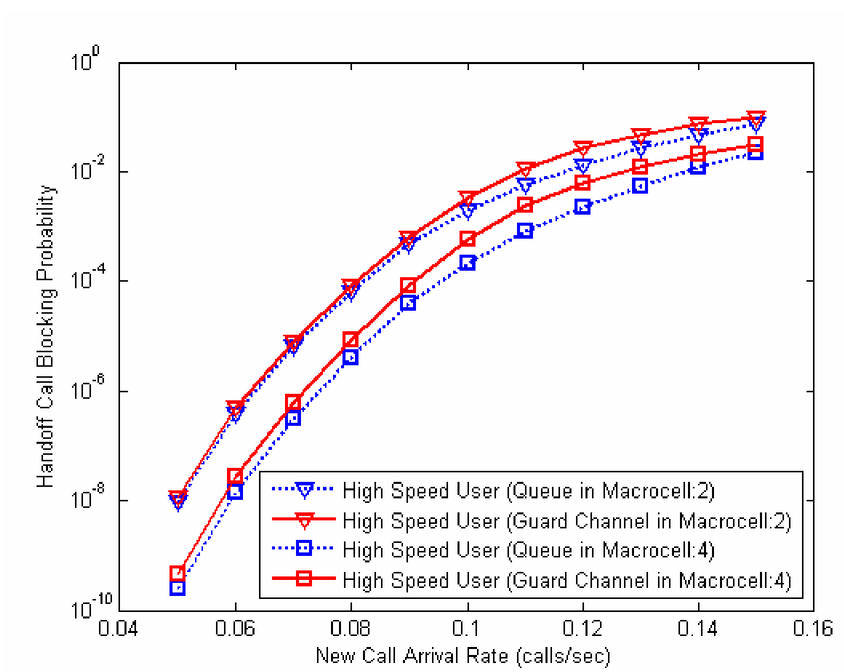

Figure 4.48 Comparison of handoff call blocking probabilities for high speed users with different queue and guard channel sizes.

4.11 NUMERICAL RESULTS FOR COMPARISON OF TWO-TIER NETWORKS WITH FIFO QUEUE AND GUARD CHANNELS IN MICROCELL

In this section, the results obtained for a two-tier network with a FIFO queue in the microcell and a two-tier network with guard channels in the microcell utilized by two user types are compared.

The comparison of the new call blocking probability for low speed users is shown in Figure 4.49. The existence of a queue or guard channels in the microcell has similar effect on the new call blocking probability of low speed users.

The comparison of the handoff call blocking probability for low speed users can be observed in Figure 4.50. A network with a queue has lower handoff call blocking probability than a network with guard channels in the microcell for low speed users. Also, as the queue or guard channel size increases the handoff call blocking probability decreases.

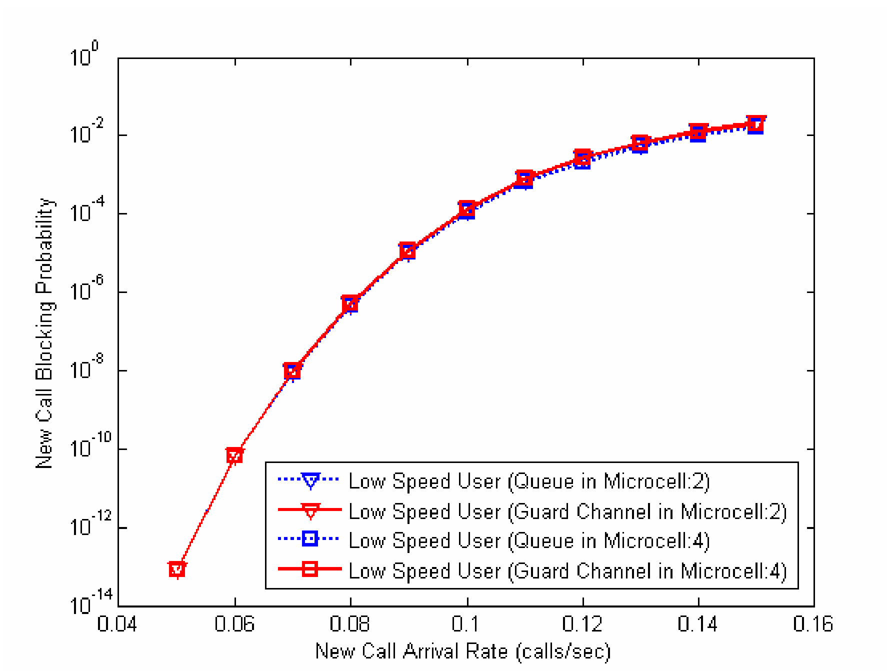

Figure 4.49 Comparison of new call blocking probabilities for low speed users with different queue and guard channel sizes.

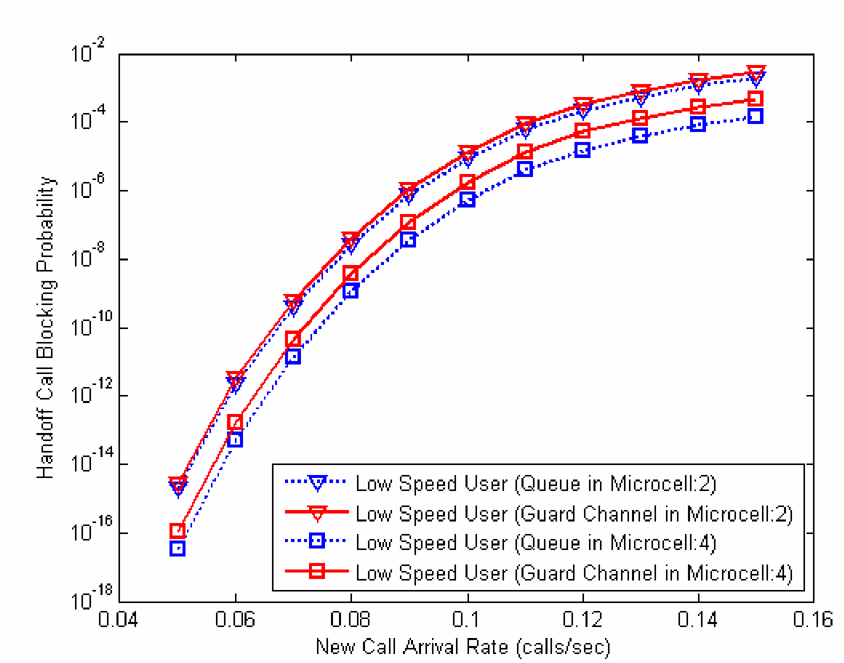

Figure 4.50 Comparison of handoff call blocking probabilities for low speed users with different queue and guard channel sizes.

The comparison of the new call blocking probability for high speed users is presented in Figure 4.51. The existence of a queue or guard channels in the microcell has similar effect on the new call blocking probability of low speed users.

Figure 4.52 shows the comparison of the handoff call blocking probability for high speed users. Since there are no queue or guard channels in the macrocell, the handoff call blocking probability is the same as the new call blocking probability.

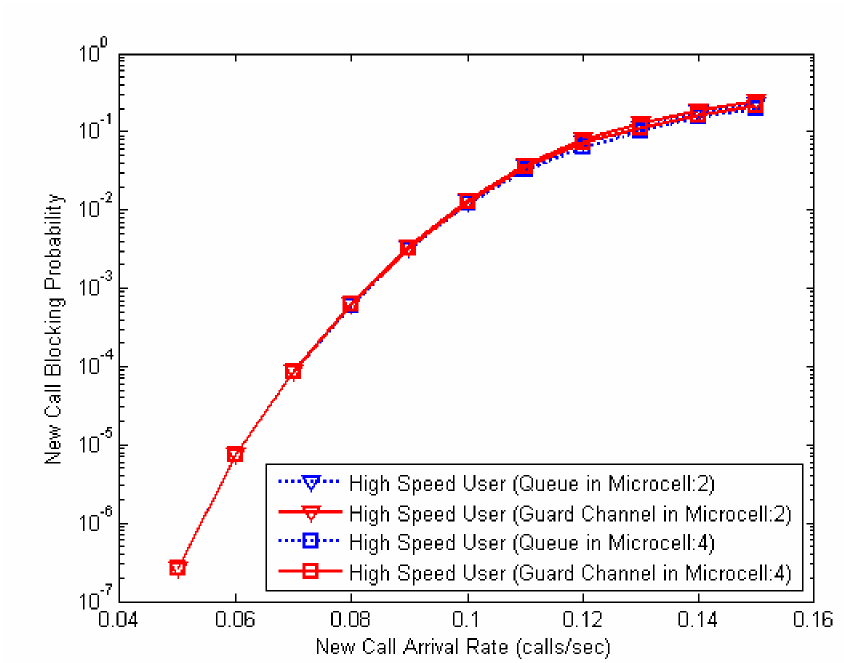

Figure 4.51 Comparison of new call blocking probabilities for high speed users with different queue and guard channel sizes.

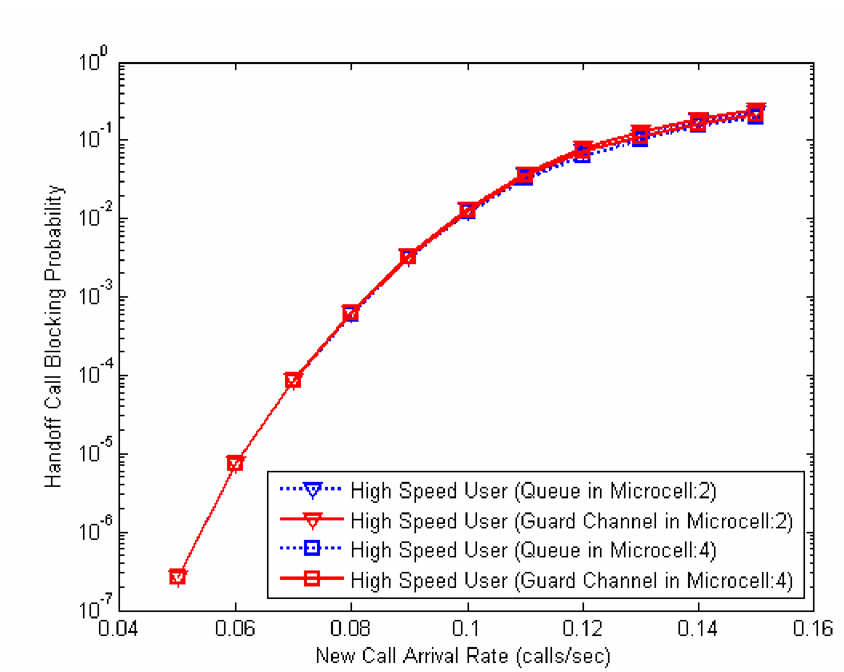

Figure 4.52 Comparison of handoff call blocking probabilities for high speed users with different queue and guard channel sizes.

4.12 NUMERICAL RESULTS FOR COMPARISON OF TWO-TIER NETWORKS WITH GUARD CHANNELS IN MICROCELL / MACROCELL

In this section, the results obtained for a two-tier network with guard channels in the microcell and a two-tier network with guard channels in the macrocell utilized by two user types are compared.

The comparison of the new call blocking probability for low speed users is shown in Figure 4.53. The new call blocking probability for low speed users in a network with guard channels in the macrocell is slightly better than the corresponding network with guard channels in the microcell.

The comparison of the handoff call blocking probability for low speed users is presented in Figure 4.54. The handoff call blocking probability of low speed users in a network with guard channels in the microcell is lower than the corresponding network with guard channels in the macrocell. This effect is due to the fact that the guard channels in the microcell are assigned to the low speed users only. Furthermore, as the number of guard channel increases the handoff call blocking probability decreases.

The comparison of the new call blocking probability for high speed users can be observed in Figure 4.55. The new call blocking probability for low speed users in a network with guard channels in the microcell is slightly better than the corresponding network with guard channels in the macrocell.

Figure 4.56 shows the comparison of the handoff call blocking probability for high speed users. The handoff call blocking probability of high speed users in a network with guard channels in the microcell decreases very slightly as the number of guard channels increases. The handoff call blocking probability of high speed users in a network with guard channels in the macrocell has much lower probability than the corresponding network with guard channels in the microcell. This effect results from the fact that high speed users in a network with guard channels in the microcell can not utilize the guard channels.

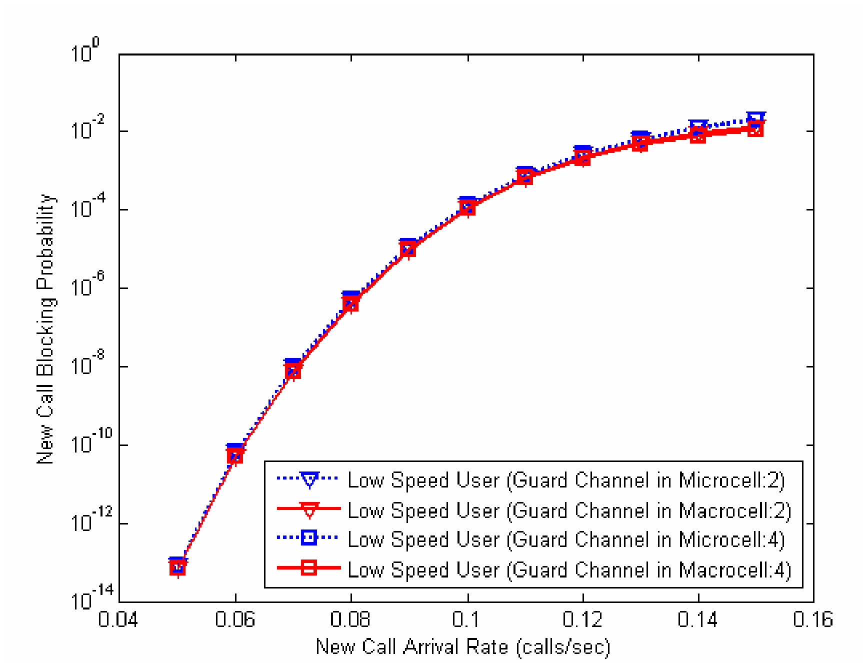

Figure 4.53 Comparison of new call blocking probabilities for low speed users with different guard channel sizes in two tier networks with guard channels.

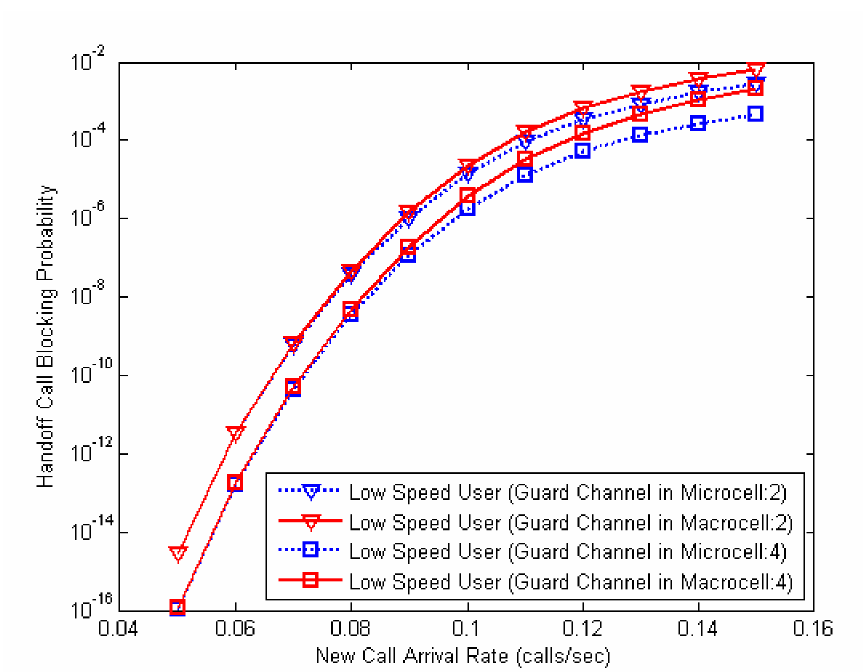

Figure 4.54 Comparison of handoff call blocking probabilities for low speed users with different guard channel sizes.

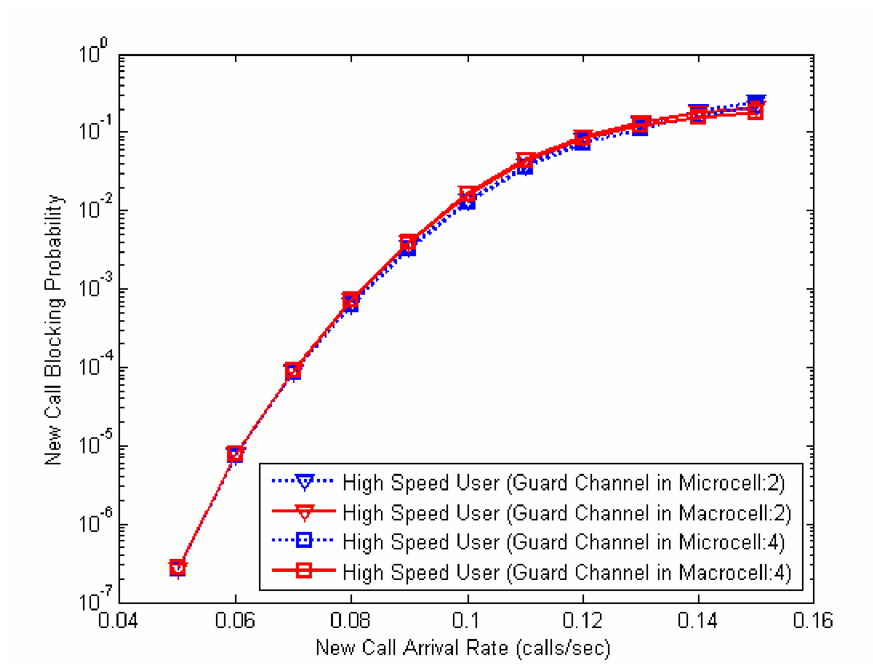

Figure 4.55 Comparison of new call blocking probabilities for high speed users with different guard channel sizes.

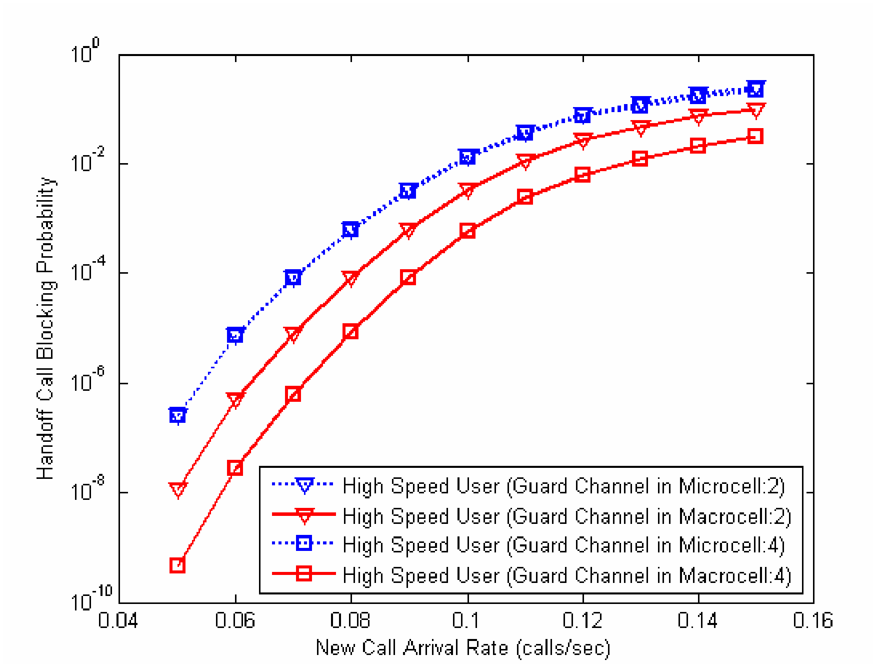

Figure 4.56 Comparison of handoff call blocking probabilities for high speed users with different guard channel sizes.

CHAPTER 5

CONCLUSIONS

In this thesis, we have improved and implemented the models for two-tier cellular networks with a FIFO queue in one of the tiers developed by (Salih, 2003). In the evaluation of the models, we have added the handoff dropping probability for each type of user. We also calculated the steady state probabilities for networks having guard channels in the microcell or the macrocell tier. So, we could compare the efficiencies of both types of cellular networks: Networks with FIFO queue and networks employing guard channels. All the network models are analyzed using single and multidimensional Markov chains and steady state probabilities are computed for calculating the performance metrics: New call blocking probability, handoff call blocking probability and handoff dropping probability.

The aim of all types of networks is to decrease handoff call blocking and handoff dropping probabilities since continuation of an active call is the most important parameter of a cellular network.

When a FIFO queue is presented in a cellular network, handoff calls are given priority by waiting handoff calls which could find any available channel in the target cell. Whenever a channel is released, it is given to the longest waiting handoff call in the queue. So, the new calls are given the second priority and can acquire a channel in the case when any free channels exist in the network. The cost of giving higher priority to handoff calls results in a slight increase in the new call blocking probability.

The guard channels technique also gives the handoff calls a priority by assigning a number of guard channels that can be used only by handoff calls. The channels available for handoff calls are higher than those of new calls.

The queue times for both types of users in each layer are supposed to be different as in (Salih, 2003) which increases the systems performance. It is shown that the handoff dropping probability for low speed users is lower when the queue is in the macrocell compared to the network having queue in the microcell. The result is due to the fact that the low speed user stays in the macrocell's queue longer than the queue in the microcell.

We compared the results of two tier cellular networks with a FIFO queue in the microcell and the macrocell. It is shown that handoff call blocking probability for low speed users is better when the queue is presented in the microcell and handoff blocking probability for high speed users is lower when the queue is presented in the macrocell. The handoff dropping probability for both types of users is lower in a network having a FIFO queue in the macrocell.

The results obtained for two tier cellular networks with guard channels either in the micrcocell or macrocell are similar to the ones obtained for networks having a FIFO queue in one tier. The only difference is that there is no comparison of handoff dropping probability since there is no need to calculate handoff dropping probability.

When the networks having a FIFO queue or guard channels in the macrocell are compared, it is seen that handoff call blocking probability for both types of users is better when a FIFO queue is used. The result is due to the effect of a call waiting in a queue performs better than providing extra channels to the cell.

When the networks having a FIFO queue or guard channels in the microcell are compared, it is seen that handoff call blocking probability for low speed users is better when a FIFO queue is used. Handoff call blocking probability for high speed users is almost identical in both networks.

Future research can be conducted in the direction of comparing our results with those obtained from simulation packages such as OPNET and NS-2. A simulation package can be used to evaluate proposed handoff algorithms on a cellular network such as AMPS or GSM.

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