Queuing-Based Dynamic Multi-Guard Channel Scheme for Voice/Data Integrated Cellular Wireless Networks

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ABSTRACT

In voice/data integrated cellular wireless networks where handoffs occur more often than earlier mobile networks, it's important to introduce a scheme that gives priority to handoff calls over new calls. From the user's perspective dropping a handoff call is less desirable than blocking a new one. Furthermore, from the service provider's point of view the objective is to improve the utilization of the wireless channel.

Motivated with these arguments, a new scheme named as (QDCRS) is proposed which combines the features of Dynamic Channel Reservation Scheme (DCRS) and Handoff Queuing Scheme (HQS). The design goal is to maintain a low dropping probability while decreasing the blocking probability and improving the system performance. Traffic is divided into four classes and priority is given in the following order: (1. handoff voice calls, 2. handoff data calls, 3. new voice calls, 4. new data calls). The boundary between traffic classes is dynamically adjusted according to the mobility of calls and status of the network. Moreover, there is a queue (Q) with capacity (K) for handoff data calls. There is no similar queue for other classes of traffic. The proposed scheme is modeled by a two-dimensional Markov chain in order to obtain the steady state probabilities of the system. Performance of the proposed scheme is investigated in terms of blocking/dropping probabilities and channel utilization.

Results obtained analytically and through simulation indicate that the proposed scheme exhibits the best Grade of Service (GoS) cost function and performance/cost (Z) function values, compared to the well-known Fully Shared Scheme (FSS) and the Guard

Channel Scheme (GCS) and it maintains its superiority under heavy load and variant mobility.

Keywords: Voice/data integrated cellular networks, Dynamic channel reservation, Handoff queuing, Quality of Service (QoS).

ÖZ

Entegre ses/veri hücresel kablosuz ağlarda, hücreler arası transferi daha sık oluştuğu için, hücreler arası transfer çağrıları yeni çağrılardan daha öncelik veren bir tasarı önermek çok önemlidir. Kullanıcı açısından devam eden bir çağrı kesmek yeni bir çağrı engellemekten daha az tercih edilmektedir. Ayrıca, hizmet sağlayıcının açısından bakıldığında kablosuz kanallar kullanımını artırmak en önemli amacı olduğunu belinmektedir.

Yukarıdaki düşüncelerden motive edilerek, dinamik kanal ayırma yöntemi (DCRS) ve hücreler arası transfer çağrıları sıralama yonteminin (HQS) birleştiren yeni bir yöntem (QDCRS) önerilmiştir. Bu yöntemin ana hedefi düşük çağrı bırakma olasılığı korumakla birlikte yeni çağrı engelleme olasılığı azaltmak ve sistem performansını iyileştirmektir. Bu yontemede trafik dört sınıfa ayrılmıştır ve aşağıdaki sıraya göre öncelik verilir: 1. hücreler arası transfer ses çağrıları, 2. hücreler arası transfer veri çağrıları, 3. yeni ses çağrıları, 4. yeni veri çağrıları. Trafik sınıfları arasındaki sınır arama hareketliliği ve ağ durumunu göre dinamik olarak ayarlanılmaktadır. Ayrıca, hücreler arası transfer veri çağrıları için (K) kapasiteli bir kuyruk (Q) vardır. Diğer trafik sınıflar için öyle bir sıra yoktur. Önerilen tasarı, sistemin kararlı-durum olasıkları değerlerini elde etmek için, iki boyutlu bir Markov zinciri ile modellenmiştir. Önerilen QDCRS yönteni performans engelleme/bırakma olasılıklar ve kanal kullanımı açısından incelenmiştir.

Kapsamlı benzetim ve analitik çalışmaları sonucunda elde edilen performans değerlendirme sonuçları, önerilen tasarının, literatürde önerilen diğer yöntemlerden (FSS ve GCS) daha iyi olduğunu göstermektedir, ve bu üstünlüğü değişken hareketlilik ve ağır yük altında sürdürmektedir.

Anahtar Kelimeler: Ses/veri bütenleşmiş hücresel ağları, Dinamik kanal ayırma, hücreler arası transfer sıralama, hizmet kalitesi (QoS).

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INTRODUCTION

1.1 Cellular Architecture

Figure 1.1 shows the structure of a voice/data integrated cellular wireless network. The basic elements of a cellular wireless networks as shown in the figure are, mobile users (e.g. mobile phones, smart phones, internet-enabled phones and PDAs), base station and wireless links. Base stations are established at the middle of each cell, they act as an intermediate between mobile users and wired networks. In other words, they're responsible for transferring packets between mobile users and the wired network. Finally, wireless links are used to connect mobile users to the base station [1] and [2].

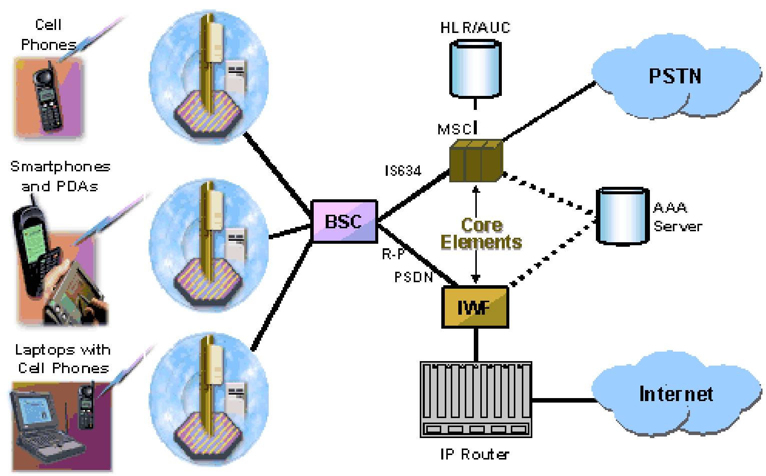

Figure 1.1 Cellular Wireless Network Diagram[1]

1.2 Handoff in Cellular Wireless Networks

The handoff process (also called handover) is enforced when an ongoing call is transferred from one cell to another, if no channels are available in the neighboring cell to serve the handoff call, the call is forced into termination (call dropping) [3]-[6].

The handoff area is defined as the region between the handover threshold and the receiver threshold [7].

Handoff calls can be classified into two types as shown in Figure 1.2, hard handoff where the mobile user gives back its channel to the old base station before getting a channel from the new base station, and soft handoff where the mobile user gets a channel from the new base station before releasing its channel [2].

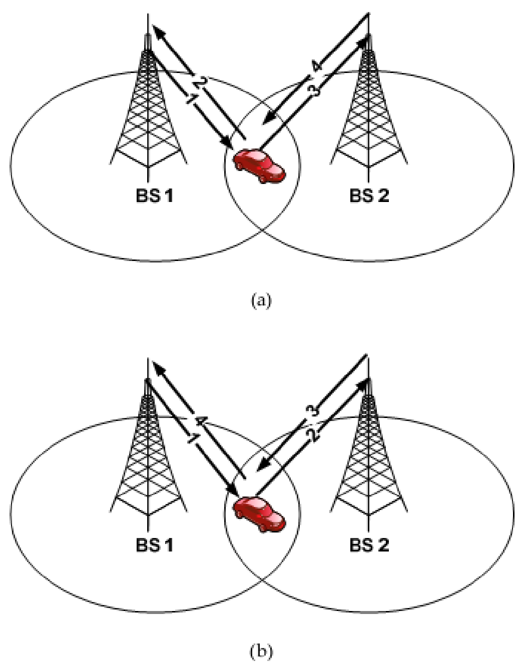

Figure 2.2 (a) hard handoff, (b) soft handoff[2]

Handoff management can be classified into two methods, guard channel method and queue method. The guard channels maybe fixed or dynamically allocated based on mobility of calls, fixed guard channels may waste frequency spectrum in case of low mobility of calls whereas dynamically allocated guard channels can use the frequency spectrum efficiently. The queue method may suit non real-time traffic (i.e. data) where delays can be tolerated but may not suit real-time traffic (i.e. voice) [8].

1.3 Problem Definition and Motivation

In order to measure the performance of the cellular wireless network, three Quality of Service (QoS) parameters are considered, the new call blocking probability (Pb), the handoff call dropping probability (Pd) and the system utilization (U). From the user's perspective the aim is to reduce the handoff dropping probability and the new call blocking probability, while from the service provider's point of view the aim is to maximize the utilization of the system. Therefore, the objective in designing channel allocation schemes is to make a fair balance between both the user and the service provider satisfaction [5].

For a mobile user is a cellular wireless network, the dropping of a handoff call is less desirable than blocking a new call, and hence handoff calls take a priority over new calls [9] and [10].

In general, channel allocation schemes can be divided into non prioritized and prioritized schemes. The well-known non prioritized is the Fully Shared Scheme (FSS), which does not discriminate between handoff and new calls. FSS reduces the new call blocking probability and gives higher system utilization of the channels available. However, FSS doesn't guarantee the targeted dropping probability in voice/data integrated cellular wireless networks where the handoff event may occur more frequent than earlier mobile networks [11] [12].

On the other hand, the well-known prioritized scheme is the Guard Channel Scheme (GCS), in which guard channels are reserved only for handoff calls, while the normal channels are shared between handoff and new calls with no distinction. GCS can maintain a low dropping probability but it results in increasing the blocking probability since new calls can't allocate the channels reserved for handoff calls, another disadvantage of GCS is that at low mobility of calls, it doesn't efficiently utilize the available channels because only a few guard channels are utilized while the others remain idle (wasted bandwidth) [13] and [14].

A Dynamic Channel Reservation Scheme (DCRS) is presented based on the concept of channel reservation. In DCRS the channels reserved for handoff calls are dynamically allocated based on the mobility of calls, allowing new calls allocate guard channels with a certain probability. The acceptance probability is determined according to the mobility of calls, the total number of available channels, threshold between normal and guard channels, and the current number of occupied channels in the cell. At high mobility (handoff calls rate is larger than new calls rate), the acceptance probability is reduced in order to give more channels to handoff calls. In this case, DCRS will act similar to GCS. On the other hand, at low mobility, the acceptance probability is increased to give more channels to new calls. In this case, DCRS will act similar to FSS. When the rate of handoff calls to new calls equals one, the guard channel is shared between handoff and new calls with no distinction [12].

DCRS can attain a low dropping probability that guarantees the targeted dropping probability while reducing the blocking probability and increases the utilization of the system. DCRS outperforms GCS in terms of blocking probability and channel utilization.

Another prioritized scheme is the Handoff Queuing Scheme (HQS), where there is a queue dedicated to handoff calls while there is no similar queue for new calls. Handoff calls can be queued for maximum the dwell time (time a mobile user spends in the handoff region). A handoff call is dropped if it finds no available channel and queue is full or it actually leaves the queue before getting a channel (forced termination) [15]. New calls are assigned a channel when channel is available and no handoff requests waiting in the queue. HQS may not suit real-time traffic when delays are inevitable but it still can suit non real-time traffic where delays can be tolerated. HQS has the advantage of decreasing the dropping probability and increasing the call-completion probability [16].

Based on the above discussion, the challenge in channel allocation in voice/data integrated networks is to find a kind of compromise between the user satisfaction and the service provider satisfaction. Therefore, it's important to present a scheme that can attain a low dropping probability, reduce the blocking probability and increase the system utilization.

1.4 Objectives

The aim of this research is to present a scheme that guarantees the targeted QoS in voice/data integrated cellular wireless networks. The proposed scheme (QDCRS) is a hybrid scheme combines the features of both the DCRS and the HQS. Four classes of traffic are considered. Priority is given as follows (1. handoff voice calls, 2. handoff data calls, 3. new voice calls, 4. new data calls). The channel is divided into four regions, T1 is the boundary between new data calls and new voice calls, T2 is the boundary between new voice calls and handoff data calls and T3 is the boundary between handoff data calls and handoff voice calls. The number of guard channels is dynamically adjusted according to the mobility of calls. There is a queue (Q) with capacity (K) for handoff data calls. There is no similar queue for other classes of traffic.

Finally, the proposed scheme (QDCRS) is compared against the Fully Shared Scheme (FSS) and the Guard Channel Scheme (GCS) under different system load (ρ) and traffic mobility ($\propto$).

1.5 Thesis Outline

The remainder of this thesis is organized as follows; Chapter 2 presents the related work and literature review. Chapter 3 contains the detailed description of the proposed model (QDCRS). Furthermore, performance analysis and simulation models are presented. Chapter 4 focuses on the results obtained analytically and via simulation and their discussions and comparisons against FSS and GCS. Finally, Chapter 5 presents the conclusions and future directions.

Chapter 2

LITERATURE REVIEW

This chapter provides a survey of the literature and parallel work within the scope of the thesis. In the literature, several channel allocation techniques have been introduced. Generally, these techniques can be classified as “Prioritized Schemes” i.e. Guard Channel Scheme (GCS), Dynamic Channel Reservation Scheme (DCRS) which is an extension of GCS where guard channels are dynamically adjusted according to the system status, Handoff Queuing Scheme (HQS), and “non Prioritized Schemes”, the well-known non prioritized scheme is the Fully Shared Scheme (FSS). FSS [17] and [18]-[20] does not distinct between handoff and new calls. Thus, it gives the maximum channel utilization and minimizes blocking probability. However, FSS does not guarantee the required QoS in terms of dropping handoff calls, as dropping an ongoing call is less desirable than blocking a new one. Therefore, prioritized schemes are preferred over FSS.

In this chapter, studies concerning the prioritized schemes (GCS, DCRS and HQS) are reviewed.

2.1 Guard Channel Scheme (GCS)

In [15], handoff calls take the highest priority by assigning a number of channels exclusively for handoffs among the total number of channels in the system, while the normal channels can be shared equally by handoff and new calls. A new call is accepted if it finds the number of the available channels less than the boundary between handoff and new calls, otherwise it's blocked. On the other hand, a handoff call is accepted if it finds channel available, otherwise it's dropped and cleared out. The system model is shown in Figure 2.1.

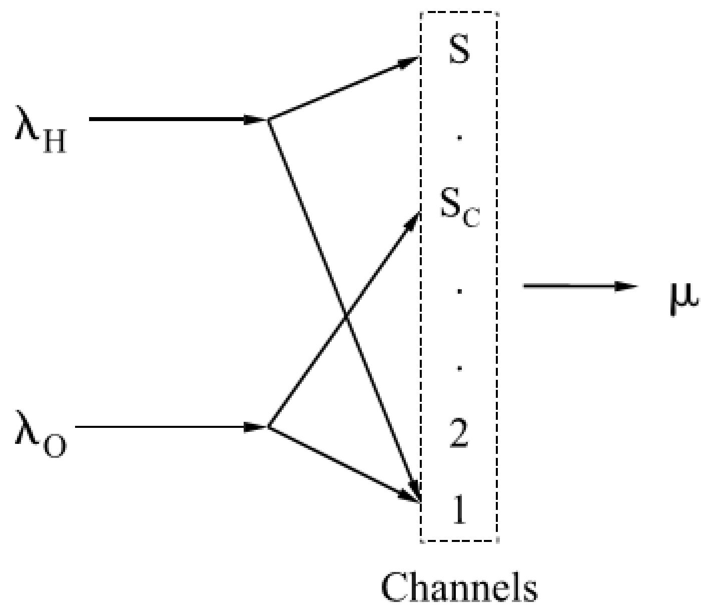

Figure 2.1 System model for GCS[15]

However, GCS can maintain a low dropping probability but it results in increasing the blocking probability since new calls can't allocate the channels reserved for handoff calls, another disadvantage of GCS is that at low mobility of calls, it doesn't efficiently utilize the available channels because only a few guard channels are utilized while the others remain idle (wasted bandwidth).

Other approaches based on the concept of GCS are presented in [15], [21] and [22].

2.2 Dynamic Channel Reservation Scheme (DCRS)

In [12], a DCRS based on mobility has been introduced. The objective is to maintain a low dropping probability while keeping the blocking probability as low as possible and improving the channel utilization. New calls can be allocated to the guard channels reserved for handoff calls as much as the acceptance probability generated according to the mobility of calls and system status. Figure 2.2 shows the Call Admission Control (CAC) flowchart for DCRS.

DCRS maintains the dropping probability at a constant level regardless of the mobility of calls. This results in improving the channel utilization and minimizing the blocking probability.

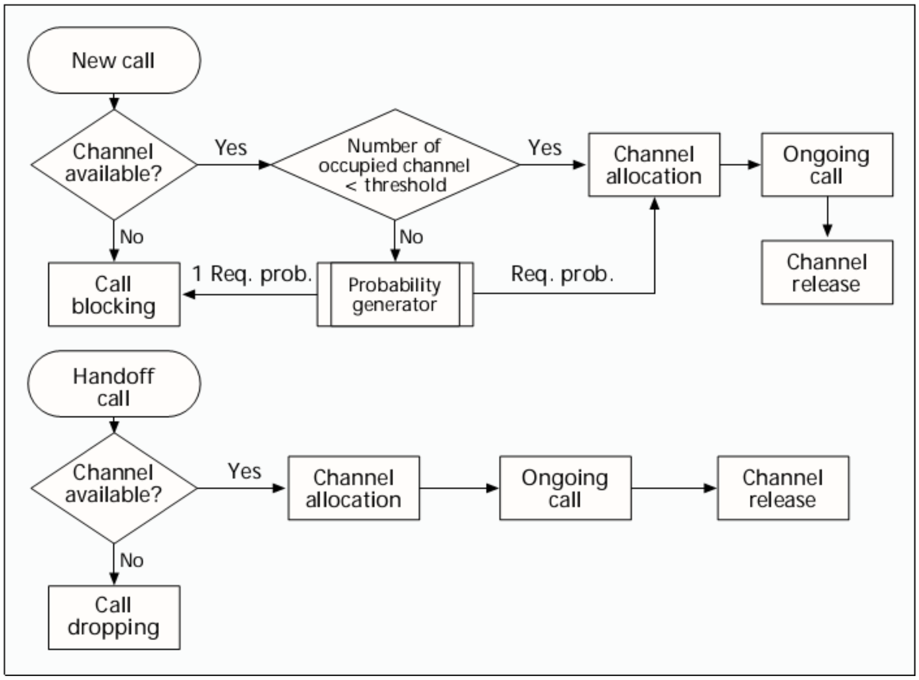

Figure 2.2 CAC flowchart for DCRS[12]

In [11], an adaptive multi-guard channel scheme (AMGCS) is proposed. The aim of AMGCS is to reserve different number of guard channels for handoffs of different classes (three classes of traffic are considered). New calls can allocate channels reserved for higher traffic classes based on a certain probability generated according to the mobility of calls, total number of channels in the system, total number of busy channels and the boundary between normal and guard channels. AMGCS can satisfy the required QoS in cellular wireless networks supporting multiple classes of traffic, by minimizing blocking/dropping probabilities, consequently the GoS cost function is also minimized.

Recently, a model proposed [23] similar to AMGCS. However, only two classes of traffic are considered (voice and data) and furthermore traffic is classified as follows, (1. handoff voice calls, 2. handoff data calls, 3. new voice calls, 4. new data calls). This scheme is able to guarantee the required QoS in cellular wireless networks providing voice/data services as it achieves low dropping probabilities and can efficiently utilize the wireless network.

Several approaches based on DCRS are also provided, like in [24], [25] and [26].

2.3 Handoff Queuing Scheme (HQS)

HQS [15] and [21], uses the same approach as GCS, except that it allows the queuing of handoff calls if necessary. However, no queuing allowed for new calls. A queued handoff call will be successful as long as a channel becomes available while waiting in the handoff area. Otherwise, it will be dropped and cleared out (forced termination). When a channel becomes available it will be allocated to the next waiting handoff attempt based on the First Come First Served queuing discipline. Figure 2.3 shows the system model for HQS.

Queuing of handoff calls can improve the dropping performance of the system along with increasing the call-completion probability.

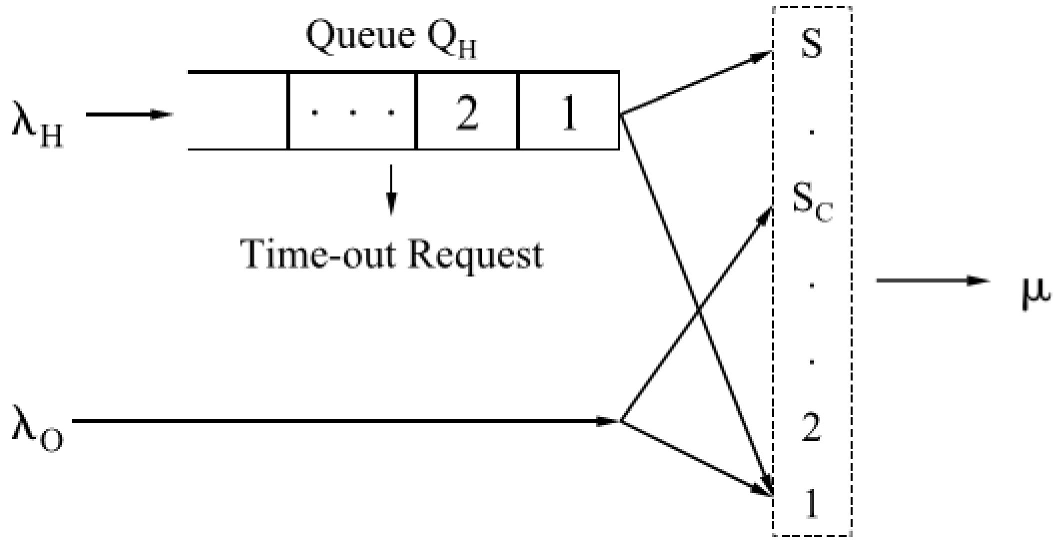

Figure 2.3 System model for HQS[15]

In [27], a multi traffic model is proposed; separate queues are dedicated for each base station of the cell and the total number of channels is shared among the base stations. Each base station is assumed to have the same number of guard channels and the same queue capacity. Consequently, a handoff attempt is held a bit longer because it can only receive service when a channel within the same base station becomes available. However, this model gives a better QoS in terms of blocking/dropping probabilities compared to HQS with a single queue.

In [28], a preemptive priority handoff scheme for voice/data integrated cellular wireless networks. Three classes of traffic are considered; handoff voice calls, new voice calls and data calls (new data calls, handoff data calls and transferred data calls). Highest priority is given to handoff voice calls. Data calls are queued if they find no available channel on their arrival. No guard channels are reserved exclusively for any class of traffic. However, a handoff voice call can preempt a data call if on arrival it finds all channels busy. An interrupted data call returns to the data queue and waits until a channel becomes available.

This scheme achieves low blocking probability of new voice call and low dropping probability of handoff voice calls and also improves the channel utilization even under heavy traffic of data.

A model proposed recently [9] based on the concept of guard channels in order to decrease the dropping probability of handoff calls. Furthermore, handoff calls are put in a finite queue if on arrival find all channels occupied. There's a threshold in the maximum waiting time spent by a handoff call. Therefore, handoff calls should not wait in queue for a very long time even if the user is still in the handoff area. Furthermore, a handoff call is dropped (forced termination) if it's dwell time (the time a mobile user spends in the handoff area) exceeds this threshold.

It's found that this scheme reduces the dropping probability of handoff calls at the expense of increasing the blocking probability of new calls and it can provide the required QoS for multimedia cellular wireless networks.

Finally, an extensive survey on Call Admission Control schemes for cellular wireless networks is presented in [29] including classification of these schemes based on various parameters (i.e. prioritized and non prioritized handoff schemes) and discussions regarding prioritized handoff schemes (i.e. handoff queuing schemes and channel reservation schemes). Furthermore, a novel Prioritized New Call Queuing (PNCQ) scheme is proposed in order to reduce the reattempt and blocking probabilities of new calls while keeping the same handoff dropping probability and system utilization. Moreover, this scheme can be combined with any handoff prioritized scheme in order to improve the performance of the system in terms of new calls reattempt and blocking probabilities. However, PNCQ is more suitable for voice calls only as it assumes other traffic classes (data and video) follow the same reattempt model which is not true for real life cellular wireless networks providing multimedia services.

Chapter 3

METHODOLOGY

3.1 System Model

In the proposed model (Figure 3.1), two classes of arrival traffic at the base station (BS) are considered; voice (real-time) and data (non real-time) calls. Furthermore, traffic is classified as new and handoff according to the type of request. It's assumed all cells are statistically identical, and therefore a single cell is considered as the reference cell. It's also assumed each admitted call of any type (handoff voice call, handoff data call, new voice call, new data call) requires one channel. The total number of channels in a cell is 'C' divided into four regions, T1 is the boundary between new data calls and new voice calls, T2 is the boundary between new voice calls and handoff data calls and T3 is the boundary between handoff data calls and handoff voice calls. The reservation thresholds are dynamically adjusted according to the mobility of calls. There is a queue (Q) with capacity (K) for handoff data calls. There is no similar queue for voice calls (new and handoff) and new data calls.

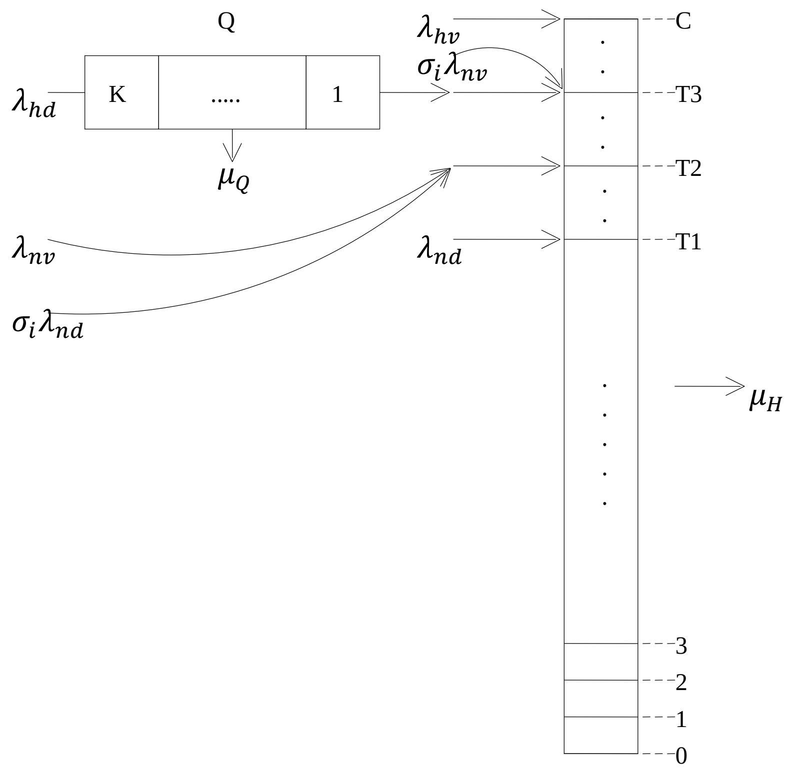

Figure 3.1 System model

3.1.1 Voice Call Admission Control

A new voice call is accepted with probability one and assigned a channel if on arrival less than T2 channels were occupied; otherwise, if not all channels are occupied, it will enter the region reserved for handoff data calls (T3-T2) with probability σ_i as shown in (equation 3.1), the acceptance probability of a new call entering the guard channels reserved for handoff calls is dynamically determined considering the current number of occupied channels (i), mobility of calls (α), the boundary between handoff data calls and new voice calls (T2) and the boundary between handoff voice calls and handoff data calls (T3)[11] and [12]. A new voice call will be blocked if it finds (C-T3) channels occupied.

$$\sigma_i = \begin{cases} MAX\left(0, \alpha\left[\dfrac{T2-i}{T2-T1}\right] + (1-\alpha)\left[\cos\dfrac{2\pi(i-T1)}{4(T2-T1)}\right]^{1/2}\right), & T1 \le i \le T2-1 \\ MAX\left(0, \alpha\left[\dfrac{T3-i}{T3-T2}\right] + (1-\alpha)\left[\cos\dfrac{2\pi(i-T2)}{4(T3-T2)}\right]^{1/2}\right), & T2 \le i \le T3-1 \end{cases} \quad (3.1)$$

When a handoff voice call arrives it will be accepted and assigned a channel if it finds channel available; otherwise, it will be dropped and cleared out.

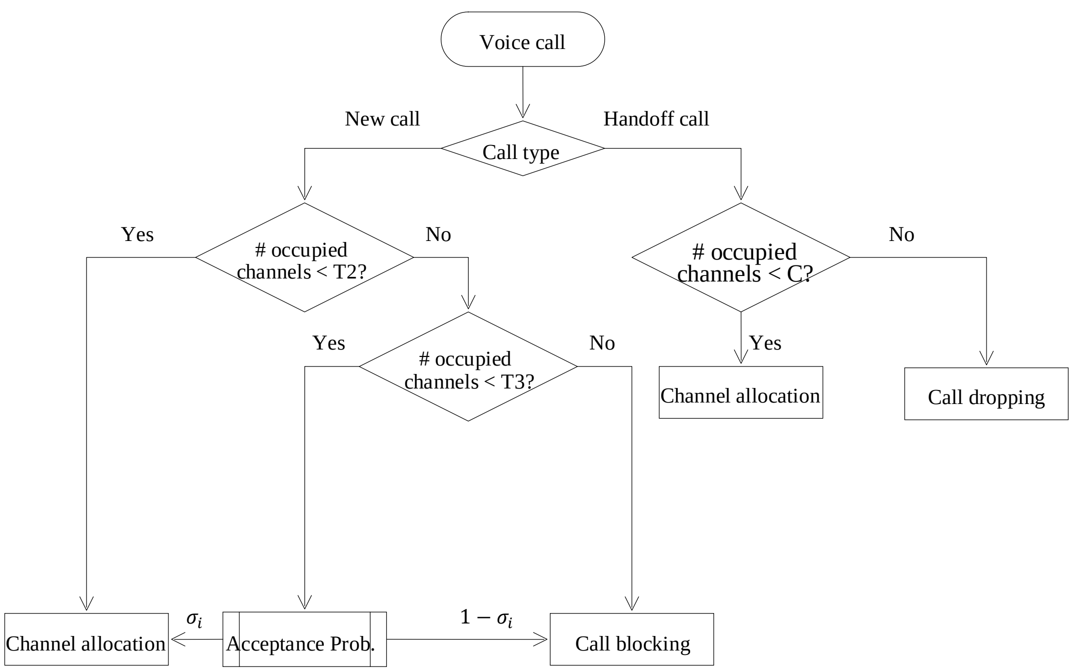

Figure 3.2 Voice call admission control

Figure 3.2 shows the voice call admission control flow diagram.

3.1.2 Data Call Admission Control

New data calls arriving at the base station (BS) are accepted if the total number of occupied channels is less than T1, else they will be accepted as much as the acceptance probability (σ_i) computed by (equation 3.1) if the total number of occupied channels less than T2; otherwise, they are blocked.

On the other hand, arriving handoff data calls are admitted if the total number of busy channels is less than T3. If the handoff call finds no available channel it will be queued for maximum T_Q (the dwell time of a MS in the handoff area). For simplicity of analysis this time is assumed to be exponentially distributed with mean $\overline{T_Q}$ ($=\frac{1}{\mu_Q}$) [21]. If a channel becomes available within T3 it will be assigned to a queued handoff data call on FIFO basis. A handoff data call is dropped if it finds no available channel and queue is full or it actually leaves the queue before getting a channel (forced termination).

Figure 3.3 shows the data call admission control flow diagram.

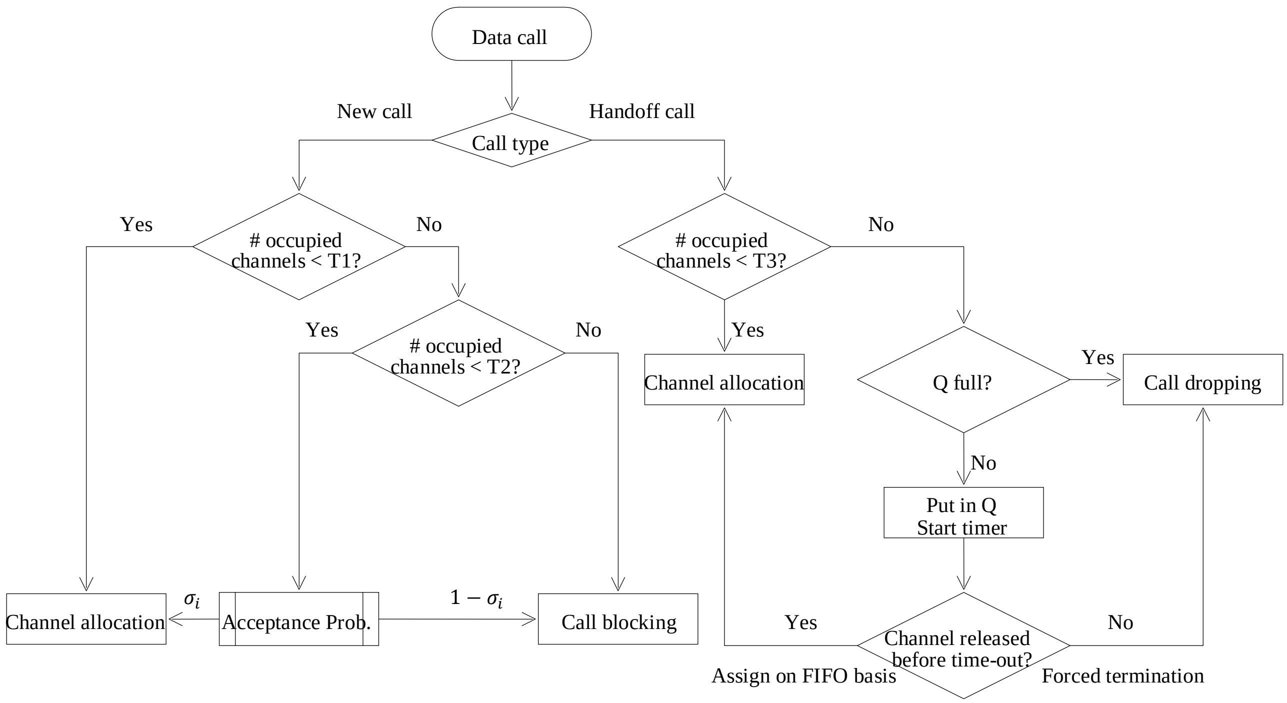

Figure 3.3 Data call admission control

3.2 Analytical Model

Arriving calls at the BS are assumed to be generated according to a Poisson process with mean arrival rates per cell $\lambda_v(=\lambda_{hv} + \lambda_{nv})$ and $\lambda_d(=\lambda_{hd} + \lambda_{nd})$. The total mean arrival rate is defined as [11],

$$\lambda_{total} = \lambda_v + \lambda_d \tag{3.2}$$

Channel holding time is approximated to have an exponential distributed with mean $\overline{T_H}$ $(=\frac{1}{\mu_H})$, where μ_H is the departure (service) rate.

The normalized offered load of the system is defined as,

$$\rho = \frac{\lambda_{total}}{C\mu_H} \tag{3.3}$$

The mobility of calls ($\propto$) is defined as the ratio of the mean handoff arrival rate to the mean new arrival rate, and hence the mobility of voice calls ($\propto_1$) and the mobility of data calls ($\propto_2$) is given by,

$$\propto_1 = \frac{\lambda_{hv}}{\lambda_{nv}} \tag{3.4}$$

$$\propto_2 = \frac{\lambda_{hd}}{\lambda_{nd}} \tag{3.5}$$

For simplicity of analysis, it's assumed the mobility of voice calls and the mobility of data calls are equal (i.e. $\propto_1 = \propto_2 = \propto$).

From equations (3.2), (3.3), (3.4) and (3.5), the mean arrival rates (λ_{hv}, λ_{hd}, λ_{nv} and λ_{nd}) can be found given the normalized offered load of the system and the mobility of calls.

3.2.1 System State Probabilities

The state of the system is defined by the two-tuple (i,j), where i(i=0,1,…,C) is the number of occupied channels and j(j=0,1,…,K) is the number of handoff data calls waiting in the queue (Q). Therefore, the proposed scheme (QDCRS) can be modeled by a two-dimensional Markov chain as shown in Figure 3.4. In the transition diagram there are $N_T = (C - T3 + 1)(K + 1) + (T3)$ balance equations, these equations are found as follows,

$$\begin{cases} (\lambda_v + \lambda_d)P(i-1,j) = i(\mu_H)p(i,j), & 0 < i \le T1, \quad j = 0 \\ (\lambda_v + \lambda_{hd} + \sigma_n\lambda_{nd})P(i-1,j) = i(\mu_H)p(i,j), & T1+1 \le i \le T2, \quad j = 0 \\ (\lambda_{hv} + \lambda_{hd} + \sigma_n\lambda_{nv})P(i-1,j) = i(\mu_H)p(i,j), & T2+1 \le i \le T3, \quad j = 0 \\ (\lambda_{hv})P(i-1,j) = i(\mu_H)p(i,j), & T3+1 \le i \le C, \quad j = 0 \\ (\lambda_{hd})P(i,j-1) = (i\mu_H + j\mu_Q)p(i,j), & i = T3, \quad 1 \le j \le K \\ (\lambda_{hd})P(i,j-1) = j(\mu_Q)p(i,j), & T3+1 \le i \le C, \quad 1 \le j \le K \end{cases} \tag{3.6}$$

Since the sum of all state probabilities must be equal to 1 (normalizing condition),

$$\sum_{i=0}^{T3-1} P(i,0) + \sum_{i=T3}^{C}\sum_{j=0}^{K} P(i,j) = 1 \tag{3.7}$$

The steady state probabilities of the system can be easily found by applying equation (3.6) recursively along with (3.7),

$$P(i,j)$$

$$= \begin{cases} \dfrac{(\lambda_v + \lambda_d)^i}{i!\,(\mu_H)^i} P(0,0) & , \quad 0 \le i \le T1, \quad j = 0 \\ \dfrac{(\lambda_v + \lambda_d)^{T1} \prod_{n=1}^{i-T1}(\lambda_v + \lambda_{hd} + \sigma_n\lambda_{nd})}{i!\,(\mu_H)^i} P(0,0) & , \quad T1+1 \le i \le T2, \quad j = 0 \\ \dfrac{(\lambda_v + \lambda_d)^{T1} m1 \prod_{n=1}^{i-T2}(\lambda_{hv} + \lambda_{hd} + \sigma_n\lambda_{nv})}{i!\,(\mu_H)^i} P(0,0) & , \quad T2+1 \le i \le T3, \quad j = 0 \\ \dfrac{(\lambda_v + \lambda_d)^{T1} m1 m2 \lambda_{hv}{}^{(i-T3)}}{i!\,(\mu_H)^i} P(0,0) & , \quad T3+1 \le i \le C, \quad j = 0 \\ \dfrac{(\lambda_{hd})^j}{\prod_{n=1}^{j}(i\mu_H + n\mu_Q)} P(i,0) & , \quad i = T3, \quad 1 \le j \le K \\ \dfrac{(\lambda_{hd})^j}{\prod_{n=1}^{j}(n\mu_Q)} P(i,0) & , \quad T3+1 \le i \le C, \quad 1 \le j \le K \end{cases} \tag{3.8}$$

Where $m1 = \prod_{n=1}^{T2-T1}(\lambda_v + \lambda_{hd} + \sigma_n\lambda_{nd})$, $m2 = \prod_{n=1}^{T3-T2}(\lambda_{hv} + \lambda_{hd} + \sigma_n\lambda_{nv})$ and $P(0,0)$ is the probability of the system being idle.

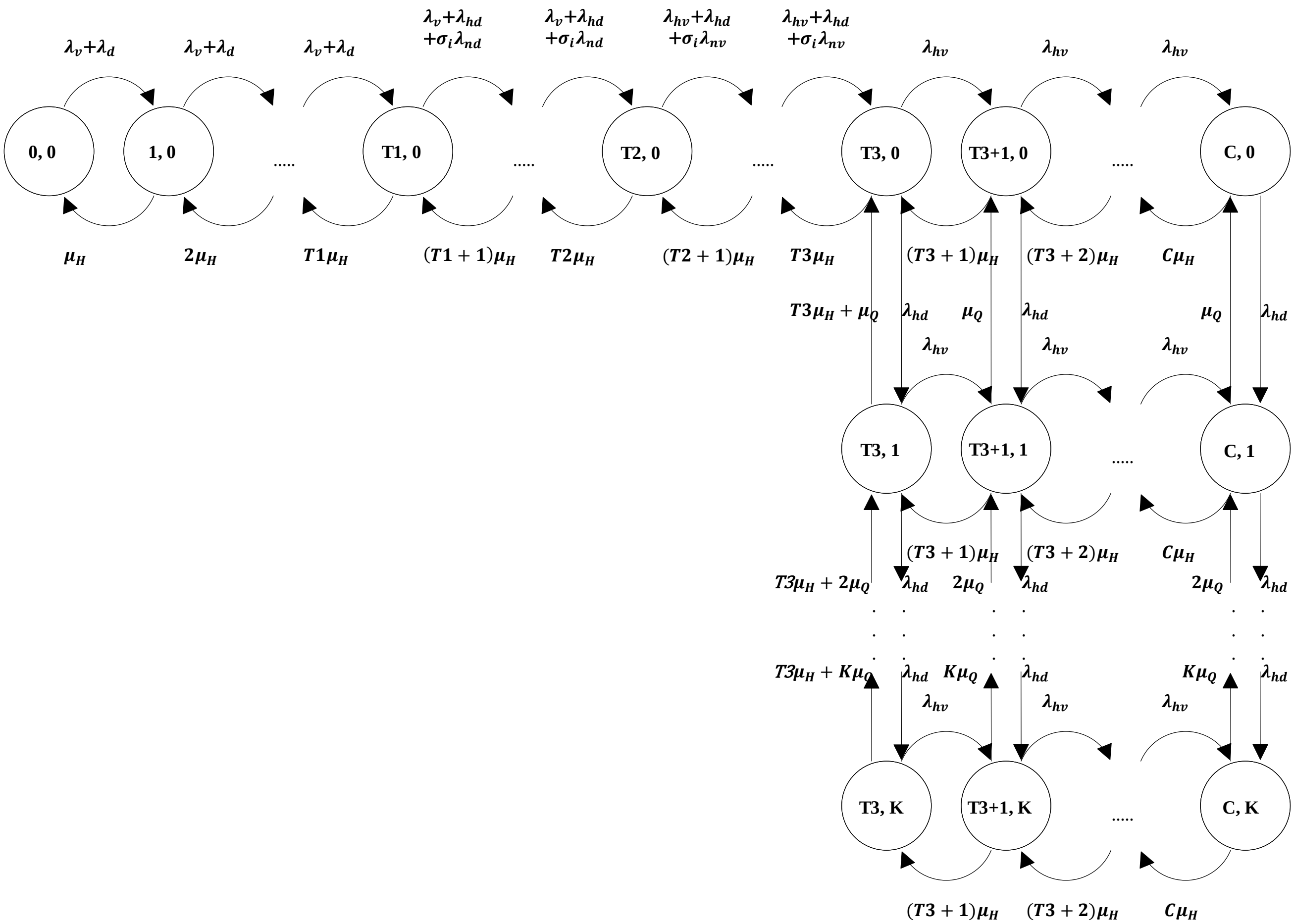

Figure 3.4 State transition diagram for QDCRS

3.2.2 Performance Measures

The performance of the proposed scheme (QDCRS) is measured in terms of blocking probability of new calls, dropping probability of handoff calls, system utilization and average waiting time in (Q) based on the steady state probabilities obtained. Furthermore, a cost function is derived in order to measure the grade of service (GoS) of the system.

The objective of the proposed scheme (QDCRS) is to attain a low dropping probability of handoff calls, reduce the blocking probability of new calls and improve the system utilization.

Blocking probability of new data calls is defined as the sum of steady state probabilities that requests for new data calls are not accepted between T1 and C, it can be expressed as the sum of steady state probabilities between T1 and (T2-1) times the complement of the acceptance probability (σ_i), plus the steady states probabilities of the system where T2 or more channels are occupied. Thus,

$$P_{bd} = \sum_{i=T1}^{T2-1} (1-\sigma_i)\, P(i,0) + \sum_{i=T2}^{T3-1} P(i,0) + \sum_{i=T3}^{C} \sum_{j=0}^{K} P(i,j) \qquad (3.9)$$

The dropping probability (P_{dd}) of handoff data calls (forced termination) is defined as the probability of all K positions of the queue (Q) are occupied, ($P_{dd'}$) plus the probability of handoff data calls that cannot get channels while waiting in (Q) (handoff failure), ($P_{dd'}$), (P_{fh}) and (P_{dd}) are given as follows,

$$P_{dd'} = \sum_{i=T3}^{C} P(i, K) \tag{3.10}$$

$$P_{fh} = \frac{1}{\lambda_{hd}} \sum_{i=T3}^{C} \sum_{j=1}^{K} P(i, j) * j * \mu_Q \tag{3.11}$$

$$P_{dd} = P_{dd'} + P_{fh} \tag{3.12}$$

Another QoS factor is the average waiting time of a handoff data call in (Q) (T_W), using Little's formula, the average waiting time in (Q) is given by,

$$T_W = \frac{L_Q}{\lambda_{hd}(1 - P_{dd'})} \tag{3.13}$$

Where (L_Q) is the average queue length,

$$L_Q = \sum_{j=1}^{K} j \sum_{i=T3}^{C} P(i, j) \tag{3.14}$$

Blocking probability of new voice calls (P_{bv}) is found similar to (P_{bd}), and is expressed as the sum of steady states between T2 and (T3-1) times the complement of the acceptance probability (σ_i) plus the sum of steady state probabilities between T3 and C,

$$P_{bv} = \sum_{i=T2}^{T3-1} (1 - \sigma_i)\, P(i, 0) + \sum_{i=T3}^{C} \sum_{j=0}^{K} P(i, j) \tag{3.15}$$

And the dropping probability of handoff voice calls (P_{dv}) is defined as the probability that all channels are occupied and can easily found by,

$$P_{dv} = \sum_{j=0}^{K} P(C, j) \tag{3.16}$$

System utilization is another important factor of performance measures and is defined as the average fraction of active servers in the system. That is,

$$U = \frac{1}{c}\left(\sum_{i=1}^{T3-1} i * P(i, 0) + \sum_{i=T3}^{C} \sum_{j=0}^{K} i * P(i, j) \right) \tag{3.17}$$

Since the objective is to minimize the grade of service (GoS) cost function (the cost function is an empirical measuring way of system's quality of service (QoS) [26]). The cost function used reflects the importance of dropping probability over blocking probability from the user's point of view, therefore the cost function is expressed as,

$$GoS = \beta P_{dv} + P_{bv} + \beta P_{dd} + P_{bd} \tag{3.18}$$

Where parameter (β = 10) indicates the penalty weight for dropping a handoff call over blocking a new one [23].

In addition to the mentioned grade of service (GoS) cost function, a new cost function is developed similar to the cost function proposed in [5] taking into consideration the system utilization along with the dropping and blocking probabilities.

The performance of the system can be defined as a function of GoS. More specifically,

$$Performance = \frac{1}{GoS} \tag{3.19}$$

From the user's point of view, in order to improve the performance of the system the value of GoS should be minimized, while from the service provider's point of view, the objective is to decrease the cost of the system by increasing the utilization of the total available channels. In other words,

$$Cost = \frac{1}{U} \tag{3.20}$$

Combining equation (3.19) and equation (3.20), a new cost function can be derived as follows,

$$Z = \frac{Performance}{Cost} \left(= \frac{U}{GoS}\right) \tag{3.21}$$

This function is a true measure of the overall system performance as it combines the blocking and dropping probabilities along with the system utilization. Since the goal is to improve the performance while decreasing the cost, the parameter Z should be maximized.

3.3 Simulation Model

Based on the description of the Call Admission Control (CAC) for voice and data calls, a Discrete Event Simulation (DES) is developed using MATLAB (Appendix B) in order to validate the analytical model. Simulation is run for long enough to reach steady-state of the system. Simulation results show a good agreement with results obtained analytically.

Simulation algorithm is illustrated in pseudo-code in Figure 3.5, the algorithm first reads in the mean arrival rates (λ_{hv}, λ_{hd}, λ_{nv} and λ_{nd}) along with the input parameters shown in Table 3.1, and initializes the following parameters; simulation time, event to be processed, time for next event (arrival/departure), number of free channels, number of handoff data calls waiting in Q, number of calls receiving service, total number of new (voice/data) calls entered, total number of handoff (voice/data) calls entered, total number of blocked (voice/data) calls, total number of dropped (voice/data) calls, total number of queued handoff data calls, area under system curve (to compute average number of busy channels), last event time, total number of timed-out handoff data calls and total queuing time.

Next, an arriving voice/data call is processed according to the Call Admission Control (CAC) flowcharts in Figure 3.3 and Figure 3.4. The service time of an admitted call and the dwell time of a queued handoff call are generated randomly from the exponential distribution with mean ($\frac{1}{\mu_H}$) and ($\frac{1}{\mu_Q}$) respectively. During each arrival event step, the times between arrivals are randomly generated from the exponential distribution with mean rates ($\frac{1}{\lambda_{hv}}$,$\frac{1}{\lambda_{hd}}$, $\frac{1}{\lambda_{nv}}$ and $\frac{1}{\lambda_{nd}}$). The timed-out handoff data call requests are removed on the arrival of a handoff data call or when a departure event occur (i.e. the two events where an operation on queue may take place). During each event step, the initialized parameters are updated as shown in Figure 3.5. The performance measures are calculated once the simulation finishes as follows;

P_{bv} = total number of blocked voice calls / total number of new voice calls entered

P_{bd} = total number of blocked data calls / total number of new data calls entered

P_{dv} = total number of dropped voice calls / total number of handoff voice calls entered

P_{dd} = (total number of dropped data calls + total number of timed-out handoff data calls) / total number of handoff data calls entered

U (normalized) = (area under system curve / total simulation time) / total number of channels (C)

T_W = total queuing time / (total number of handoff data calls entered – total number of data calls dropped)

Table 3.1: Simulation parameters

Total simulation time	$2.0 * 10^6$ sec
Mobility ($\propto$)	0.5, 1, 1.5, 2
Offered load (ρ)	0.9 Erlangs
Total number of channels	100
Threshold values (T1, T2, T3)	85, 90, 95

Mean channel holding time ($\frac{1}{\mu_H}$)	180 sec
Mean dwell time ($\frac{1}{\mu_Q}$)	4 sec
Queue size (K)	1

```
begin
while (sim_time < TOTAL_SIM_TIME)
        if (event == ARRIVAL)
                if(call_type == NEW)
                        if(voice_call)
                                update sim_time;
                                increment num_new_voice_calls_entered;
                                update area_under_system_curve;
                                update last_event_time;
                                if(num_occupied_channels < T2)
                                        channel allocation;
                                        increment num_service;
                                        decrement num_free_channels;
                                        start service;
                                else if(num_occupied_channels < T3)
                                        channel allocation with propbabiliy σ_i;
                                        if (call_accepted)
                                                increment num_service;
                                                decrement num_free_channels;
                                                start service;
                                        else
                                                call blocking;
                                                increment num_blocked_voice_calls;
                                        end
                                else
                                        call blocking;
                                        increment num_blocked_voice_calls;
                                end
                                schedule time for next new voice call arrival;
                        else if (data_call)
                                update sim_time;
```

```
                increment num_new_data_calls_entered;
                update area_under_system_curve;
                update last_event_time;
                if(num_occupied_channels < T1)
                    channel allocation;
                    increment num_service;
                    decrement num_free_channels;
                    start service;
                else if(num_occupied_channels < T2)
                    channel allocation with propbabiliy σ_i;
                    if (call_accepted)
                        increment num_service;
                        decrement num_free_channels;
                        start service;
                    else
                        call blocking;
                        increment num_blocked_voice_calls;
                    end
                else
                    call blocking;
                    increment num_blocked_data_calls;
                end
                schedule time for next new data call arrival;
            end
        else if(call_type == HANDOFF)
            if(voice_call)
                update sim_time;
                increment num_handoff_voice_calls_entered;
                update area_under_system_curve;
                update last_event_time;
                if(num_occupied_channels < C)
                    channel allocation;
                    increment num_service;
                    decrement num_free_channels;
                    start service;
                else
                    call dropping;
                    increment num_dropped_voice_calls;
                end
                schedule time for next handoff voice call arrival;
            else if(data_call)
                update sim_time;
                increment num_handoff_data_calls_entered;
                update area_under_system_curve;
                update last_event_time;
                if(any queued handoff data call timed-out)
```

```
                    drop and clear out all timed-out requests;
                    increment num_timedout;
                    update total_queuing_time;
                end
                if(num_occupied_channels < T3)
                    channel allocation;
                    increment num_service;
                    decrement num_free_channels;
                    start service;
                else if(Q NOT full)
                    put the call in Q;
                    start timer;
                else
                    call dropping;
                    increment num_dropped_voice_calls;
                end
                schedule time for next handoff data call arrival;
            end
        end
    else if(event == DEPARTURE)
        update sim_time;
        decrement num_service;
        increment num_free_channels;
        update area_under_system_curve;
        update last_event_time;
        if(any queued handoff data call timed-out)
            drop and clear out all timed-out requests;
            increment num_timedout;
            update total_queuing_time;
        end
        if(Q NOT empty)
            if(channel available for a queued handoff data call)
                assign a channel on FIFO basis;
                update total_queuing_time;
                increment num_service;
                decrement num_free_channels;
                start service;
            end
        end
    end
end
```

OUTPUT:
Blocking and dropping probabilities, system utilization and average waiting time in Q;

Figure 3.5 Simulation algorithm in pseudo-code

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Performance Results

Numerical results obtained through analytical and simulation programs are compared with the Fully Shared Scheme (FSS) and the Guard Channel Scheme (GCS). The system performance is studied under different system load (ρ) and traffic mobility ($\propto$). As mentioned earlier, FSS minimizes the blocking probability and gives higher system utilization of the available channels in the system, whereas GCS gives the minimal dropping probability but the worst utilization of the system. The proposed scheme (QDCRS) is a compromise between the two in order to guarantee the targeted QoS in voice/data integrated cellular wireless networks and to make a fair balance between both the user and the service provider satisfaction.

Input parameters used in the analytical and simulation programs are selected as follows, The total number of available channels (C = 100), the boundary between new data calls and new voice calls (T1 = 85), the boundary between new voice calls and handoff data calls (T2 = 90), the boundary between handoff data calls and handoff voice calls (T3 = 95), mean channel holding time ($\frac{1}{\mu_H} = 180\ s$), queue size (K = 1), the mean dwell time of a handoff data call is assumed to be ($\frac{1}{\mu_Q} = 4\ s$) [9], the system performance is evaluated under heavy load ($\rho = 0.9$), and mobility vary through the analysis by varying the parameter (∝), high mobility considered at (∝ = 2) and low mobility considered at (∝ = 0.5) [23] and [30].

4.1.1 Blocking Probability

Figure 4.1 shows the blocking probability of new voice calls for the three schemes under different mobility. It's clear from the figure that FSS shows constant blocking probability for all mobility values and it exhibits the minimum blocking probability except at low mobility where the proposed scheme (QDCRS) has the lowest blocking probability. It can also be seen that in QDCRS and GCS more blocking probability takes place as the mobility increases, because when the mobility of calls increases the chance of new voice calls allocating the channel is diminished. However, the QDCRS is superior to the GCS in terms of blocking probability of new voice calls.

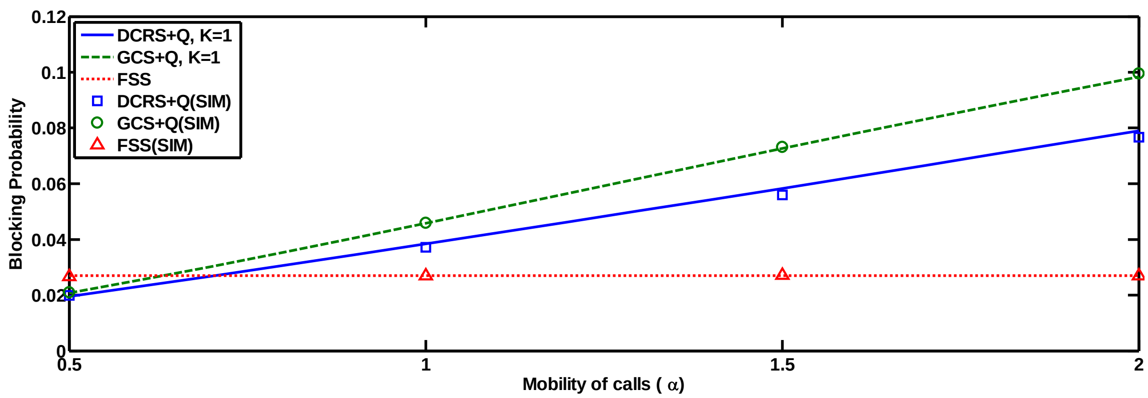

Figure 4.1 Voice blocking probability, ($\rho = 0.9$)

In Figure 4.2, the blocking probability of data calls is plotted for the three models as a function of mobility. Again and as expected, the FSS has the minimum blocking probability and it's equal to its voice blocking probability since FSS allows requests of all traffic classes to access the channel with equal probability and it shows a constant performance for the same reason. The proposed scheme (QDCRS) still outperforms the

GCS because new data calls can still be allocated to the channels reserved for the higher class of traffic as much as the acceptance probability (σ_i) computed by (equation 3.1). Again, for QDCRS and GCS when mobility increases the chance of getting a channel by a new data call decreases and this results in more blocking probability of data calls takes place.

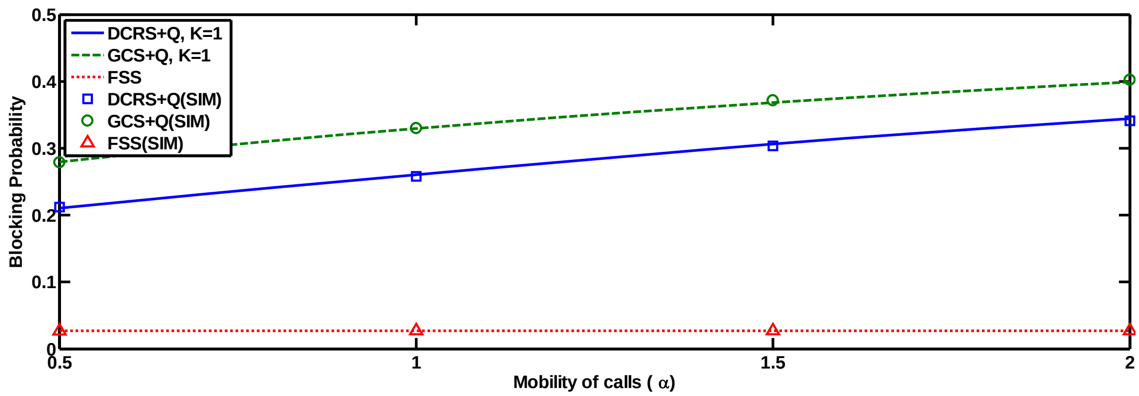

Figure 4.2 Data blocking probability, ($\rho = 0.9$)

4.1.2 Dropping Probability

Figure 4.3 presents the dropping probability of handoff voice calls (the y-axis is plotted in log-scale), it's observed from the figure that FSS has the worst dropping probability and shows a constant dropping probability for all values of mobility. It also can be seen that QDCRS and GCS satisfy a low dropping probability at high load and mobility in which most of the design problems arise. The dropping probability of both schemes is sensitive to mobility and it increases as mobility increases, this implies that the more handoff requests arrive at the system the more handoff calls could be forced into termination. However, QDCRS can satisfy the QoS of handoff voice calls and still can use the available channels efficiently unlike the GCS.

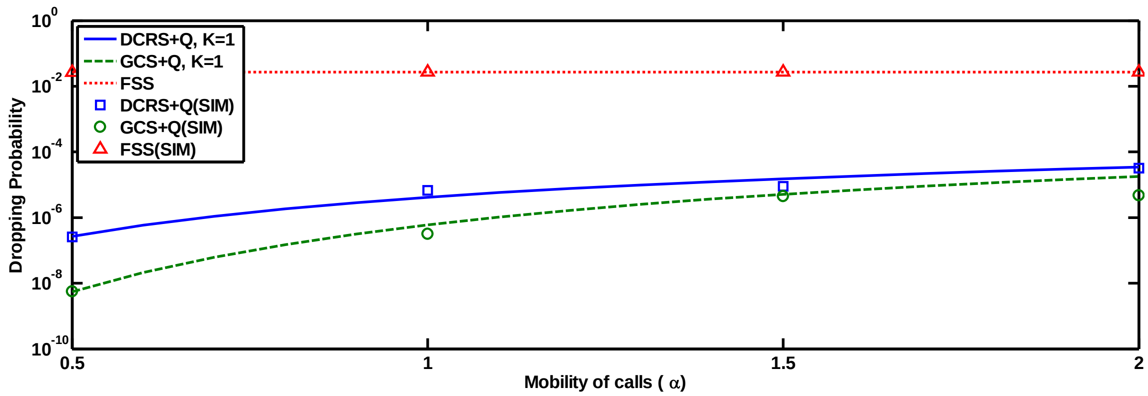

Figure 4.3 Voice dropping probability, ($\rho = 0.9$)

In Figure 4.4, the dropping probability of data calls is shown against different mobility values (the y-axis is plotted in log-scale). Again, the FSS exhibits the worst performance in terms of dropping data calls, and it's equal to its voice dropping probability since FSS treats all traffic of different classes with equal probability. It also can be seen that FSS show constant dropping probability for all values of mobility. However, FSS still can't guarantee the required dropping probability. On the other hand, both QDCRS and GCS can satisfy a low dropping probability under heavy load and high mobility, and again results show that dropping probability of data calls is sensitive to mobility that is when mobility increases dropping probability also increases and as a result more handoff data calls will be forcibly terminated.

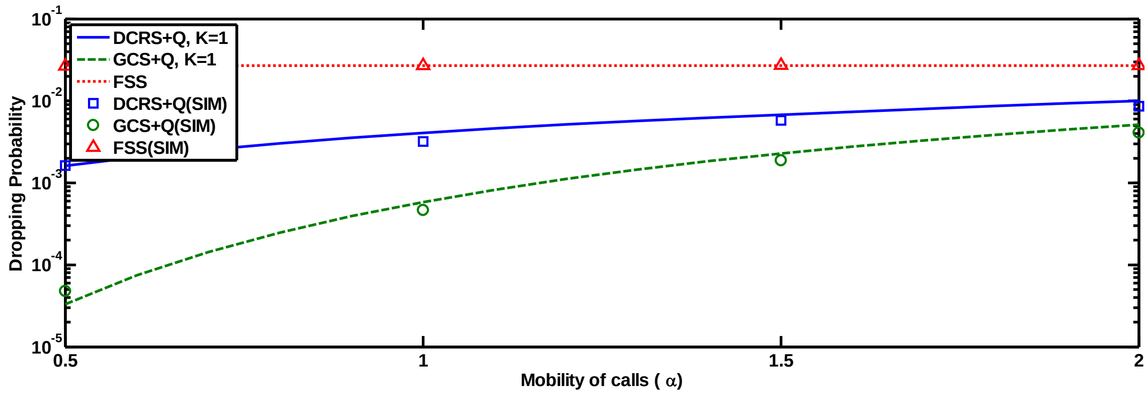

Figure 4.4 Data dropping probability, ($\rho = 0.9$)

Figure 4.5 shows the comparison between handoff data call dropping probability of the proposed scheme (QDCRS) with and without queue as a function of mobility. It's clear from the figure the effect of queue on the data dropping performance. Although a handoff data call is held a bit longer in the proposed model (QDCRS) with queue instead of immediate dropping of handoff requests finding no available channel, this results in minimizing the dropping probability of handoff data calls which guarantees the target dropping probability (1 %) and increases the call-completion probability as well. This superiority is achieved by queuing the delayed handoff requests for maximum the dwell time (T_Q, the time for which a mobile user spends in the handoff area). It's also worth to mention that increases the value of queue size (K > 1) will still preserve the value of the handoff data call dropping probability at nearly a constant value as (K = 1) for different mobility values.

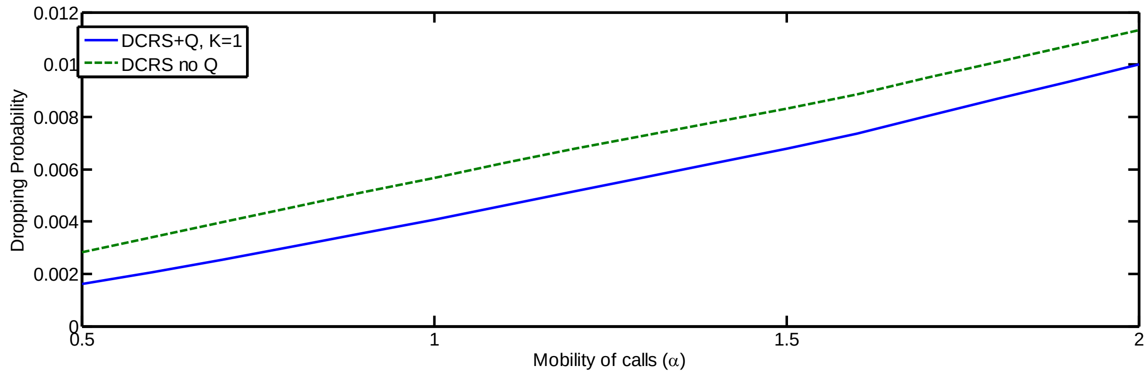

Figure 4.5 Comparison of data dropping probability with and without queue, ($\rho = 0.9$)

4.1.3 Channel Utilization

Figure 4.6 illustrates that FSS has the highest system utilization as mentioned earlier in Chapter 1. FSS shows a constant value of system utilization under different mobility of calls this due to all available channels can be assigned to calls of different classes equally. The proposed scheme (QDCRS) outperforms the GCS in terms of system utilization for all mobility values, this implies QDCRS can efficiently utilize the system resources. On the other hand, GCS has the worst channel utilization, especially at low mobility because only a few handoff calls are assigned to the channels reserved exclusively for handoff calls (voice & data) while the remaining reserved channels become idle (wasted bandwidth). The proposed scheme (QDCRS) shows a nearly constant value of channel utilization regardless of the variant of mobility, unlike the GCS where the utilization increases according to increasing the mobility of calls.

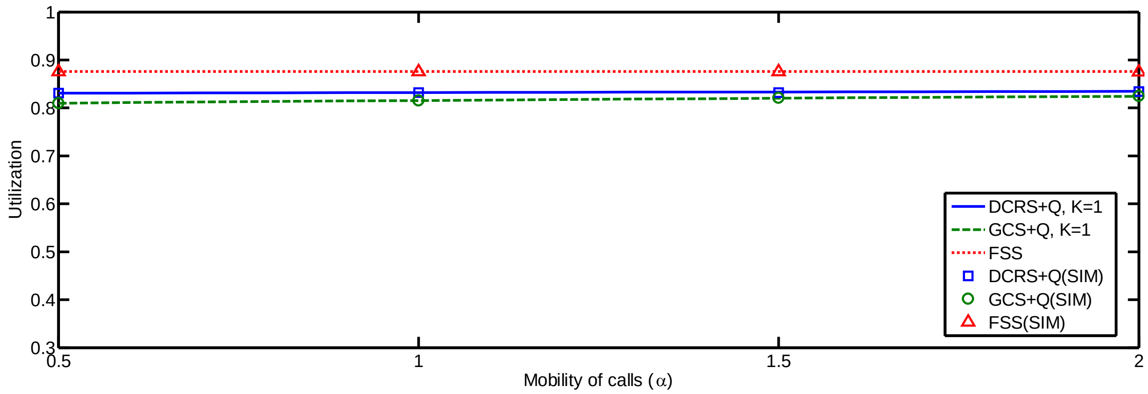

Figure 4.6 Channel utilization, ($\rho = 0.9$)

4.1.4 Average waiting time in queue (Q)

Figure 4.7 shows the average time a data handoff call spent waiting in queue (Q) before getting a channel. It can be noted from the figure that the average waiting time increases gradually according to the increase in mobility as more handoff attempts take place. Handoff data calls finding no available channels can be put in queue for maximum the time a mobile user spends in the handoff region (dwell time), this time lag doesn't actually affect the degradation of the required QoS for data calls because non real-time traffic (i.e. data) can tolerate small time delays.

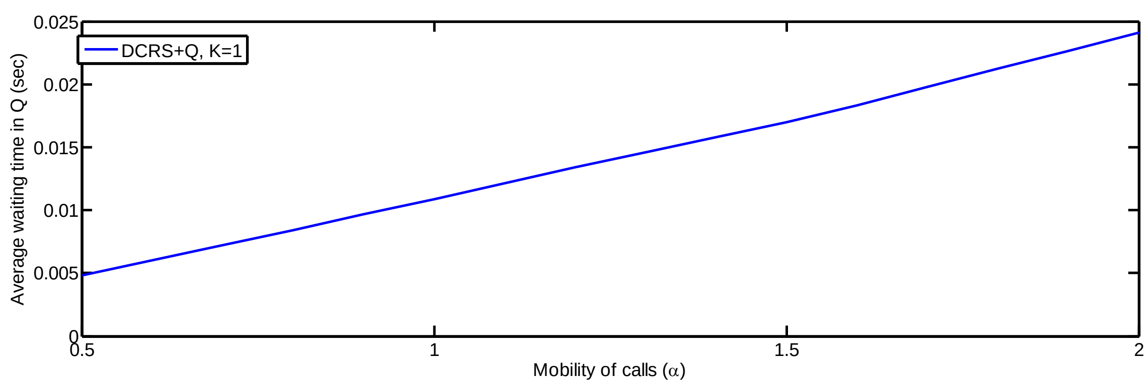

Figure 4.7 Average waiting time in queue (sec), ($\rho = 0.9$)

4.1.5 Grade of Service (GoS) Cost Function

In Figure 4.8, the GoS cost function for the three models is displayed as a function of mobility. The objective is to minimize the GoS cost function as mentioned in Chapter 3. It can be clearly seen that the proposed scheme (QDCRS) gives the best performance under heavy load and for variant mobility whereas the FSS exhibits the worst performance. The GoS for QDCRS and GCS is sensitive to mobility while for the FSS it remains constant regardless of the mobility of calls. The average GoS is 0.3858 for the proposed scheme (QDCRS), 0.4233 for the GCS and 0.5931for the FSS. Specifically, the improvement the proposed scheme (QDCRS) has over the GCS and the FSS has a mean value of 8.86 % and 34.95 % respectively.

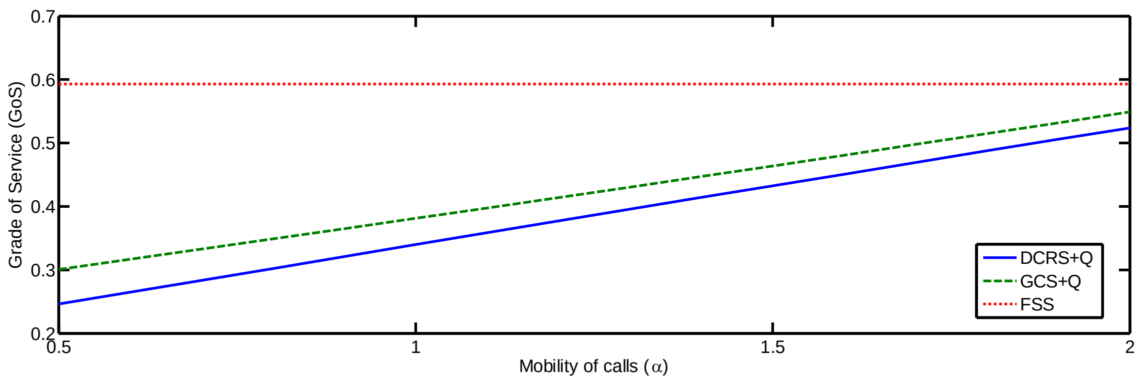

Figure 4.8 GoS cost function, ($\rho = 0.9$, $\beta = 10$)

4.1.6 Performance/Cost Ratio (Z)

In the last figure, Figure 4.9 shows the performance/cost ratio (Z) as a function of mobility. As mentioned earlier in Chapter 3, the aim is to maximize (Z). Again, the proposed scheme (QDCRS) outperforms the GCS and the FSS. As expected, the FSS has the lowest value of Z and it remains constant for different values of mobility because

FSS allows handoff and new calls share the available channels without any form of discrimination. The improvements of the proposed scheme (QDCRS) over the GCS and the FSS have mean values of 13.96 % and 54.02 % respectively.

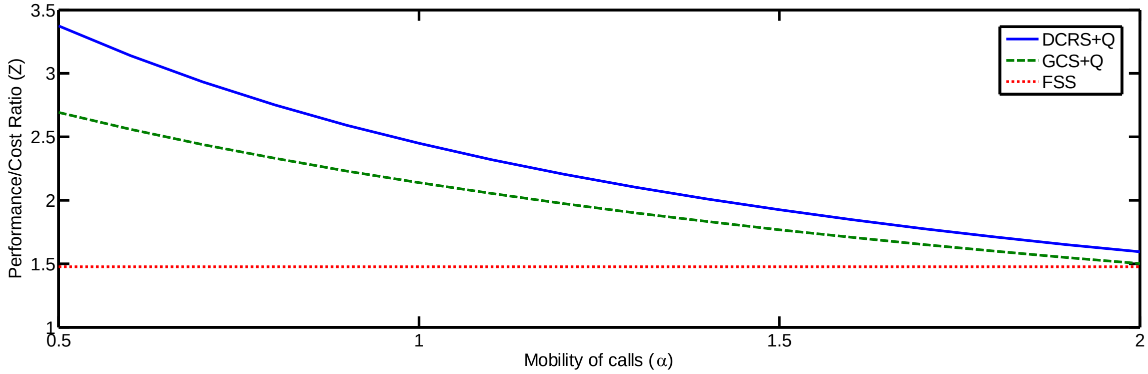

Figure 4.9 Performance/cost ratio (Z), ($\rho = 0.9$)

Chapter 5

CONCLUSION

In this thesis, a new Call Admission Control (CAC) scheme (QDCRS) is proposed for voice/data integrated cellular wireless networks based on Dynamic Channel Reservation Scheme (DCRS) and Handoff Queuing Scheme (HQS). The calls generated are divided into four different classes; priority is given in the following order (1. handoff voice calls, 2. handoff data calls, 3. new voice calls, 4. new data calls). The boundary between traffic classes is dynamically adjusted according to the mobility of calls and status of the network. Handoff data calls can be queued for maximum (T_Q) (the time a mobile user spends in the handoff area).

The performance of the proposed scheme (QDCRS) is evaluated in terms of blocking probability of new calls, dropping probability of handoff calls and channel utilization. A simulation model is developed in order to validate the analytical model derived. Results show a good agreement between performance analysis and simulation.

Results obtained analytically and through simulation show that the proposed scheme (QDCRS) which is a compromise between the Fully Shared Scheme (FSS) and the Guard Channel Scheme (GCS) can satisfy the required dropping probability for handoff voice and data calls under high load and different mobility values. Furthermore, the proposed scheme (QDCRS) can efficiently utilize the wireless channel and improve the new call blocking performance. Queuing handoff data calls can improve the dropping probability performance and therefore increase the call-completion probability.

The GoS cost function used to measure the performance of the proposed scheme (QDCRS) show it has an improvement over the GCS and FSS by a mean value of 8.86 % and 34.95 % respectively. In accordance with the GoS cost function, the performance/cost ratio (Z) derived show that the improvements of the proposed scheme (QDCRS) over the GCS and the FSS have mean values of 13.96 % and 54.02 % respectively. It can be concluded that QDCRS gives a better QoS in voice/data integrated cellular wireless network.

Finally, there are a number of issues that can be addressed in future research. The proposed model (QDCRS) can be extended to support three classes of multimedia traffic (i.e. data, voice and video). Furthermore, the mean service times may be different for different classes of traffic. Moreover, a timed-out handoff data call request in queue can be transferred to another queue in an adjacent cell within the coverage area instead of immediate dropping.

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APPENDICES

Appendix A: MATLAB Codes for Analytical Model

```
%findsigma(C, T, i, mobility)
%   This function finds the acceptance probability for new calls

function out = findsigma(C, T, i, mobility, scheme)

if(strcmp(scheme, 'DCRS') == 1)
   Sigma = max(0, mobility * ((C - i)/(C - T)) + ((1 - mobility) * sqrt(cos ((2 * pi * (i -
T)) / (4 * (C - T))))));
else
   %   For GCS, acceptance probability is always set to zero
   Sigma = 0;
end

out = Sigma;
```

```
%findp00(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the probability all channels are idle for DCRS and
%   GCS

function out = findp00(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)

[sum1, sum2] = deal(0);
MuH = 1/180;
MuQ = 1/4;
Rtotal = Rhv + Rhd + Rnv + Rnd;

for i = 0:T1
   term1 = (Rtotal^i / (factorial(i) * MuH^i));
   sum1 = sum1 + term1;
end

for i = T1+1:T2
   mobility = Rhd / Rnd;
   mult = 1;
   for m=1:i - T1
      Sigma = findsigma(T2, T1, i - m, mobility, scheme);
      mult = mult * (Sigma * Rnd + Rtotal - Rnd);
   end
   term2 = ((Rtotal^T1 * mult) / (factorial(i) * MuH^i));
   sum2 = sum2 + term2;
end
```

```
for i = T2+1:T3-1
   mobility1 = Rhd / Rnd;
   mobility2 = Rhv / Rnv;
   mult1 = 1;
   for m=1:T2 - T1
      Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
      mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
   end

   mult2 = 1;
   for m=1:i - T2
      Sigma = findsigma(T3, T2, i - m, mobility2, scheme);
      mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
   end

   term2 = ((Rtotal^T1 * mult1 * mult2) / (factorial(i) * MuH^i));
   sum2 = sum2 + term2;
end

for i=T3:T3
   if(K == 0)
      mobility1 = Rhd / Rnd;
      mobility2 = Rhv / Rnv;
      mult1 = 1;
      for m=1:T2 - T1
         Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
         mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
      end

      mult2 = 1;
      for m=1:i - T2
         Sigma = findsigma(T3, T2, i - m, mobility2, scheme);
         mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
      end

      term2 = ((Rtotal^T1 * mult1 * mult2) / (factorial(i) * MuH^i));
      sum2 = sum2 + term2;
   else
      mobility1 = Rhd / Rnd;
      mobility2 = Rhv / Rnv;
      mult1 = 1;
      for m=1:T2 - T1
         Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
         mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
      end
```

```
        mult2 = 1;
        for m=1:i - T2
            Sigma = findsigma(T3, T2, i - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end

        term2 = ((Rtotal^T1 * mult1 * mult2) / (factorial(i) * MuH^i));

        for m=1:K
            mult = 1;
            for n=1:m
                mult = mult * (i*MuH + n*MuQ);
            end
            sum2 = sum2 + Rhd^m * term2 / mult;
        end
        sum2 = sum2 + term2;
    end
end

for i=T3+1:C
    if(K==0)
        mobility1 = Rhd / Rnd;
        mobility2 = Rhv / Rnv;
        mult1 = 1;
        for m=1:T2 - T1
            Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
            mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
        end

        mult2 = 1;
        for m=1:T3 - T2
            Sigma = findsigma(T3, T2, T3 - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end

        term2 = ((Rtotal^T1 * mult1 * mult2 * Rhv^(i-T3)) / (factorial(i) * MuH^i));
        sum2 = sum2 + term2;
    else
        mobility1 = Rhd / Rnd;
        mobility2 = Rhv / Rnv;
        mult1 = 1;
        for m=1:T2 - T1
            Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
            mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
        end

        mult2 = 1;
```

```
        for m=1:T3 - T2
            Sigma = findsigma(T3, T2, T3 - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end

        term2 = ((Rtotal^T1 * mult1 * mult2 * Rhv^(i-T3)) / (factorial(i) * MuH^i));

        for m=1:K
            mult = 1;
            for n=1:m
                mult = mult * (n*MuQ);
            end
            sum2 = sum2 + Rhd^m * term2 / mult;
        end

        sum2 = sum2 + term2;
    end
end

total = sum1 + sum2;
P00 = total^-1;

out = P00;
```

```
%findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme)
%   This function finds the steady state probabilities for DCRS and GCS

function out = findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme)

MuH = 1/180;
MuQ = 1/4;
Rtotal = Rhv + Rhd + Rnv + Rnd;
P00 = findp00(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme);

if i == 0
    Pij = P00;
end

if i >= 1
    if i <= T1
        Pij = (Rtotal^i / (factorial(i) * MuH^i)) * P00;
    end
end

if i >= T1 + 1
```

```
    if i <= T2
        mobility = Rhd / Rnd;
        mult = 1;
        for m=1:i - T1
            Sigma = findsigma(T2, T1, i - m, mobility, scheme);
            mult = mult * (Sigma * Rnd + Rtotal - Rnd);
        end
        Pij = ((Rtotal^T1 * mult) / (factorial(i) * MuH^i)) * P00;
    end
end

if i >= T2 + 1
    if i < T3
        mobility1 = Rhd / Rnd;
        mobility2 = Rhv / Rnv;
        mult1 = 1;
        for m=1:T2 - T1
            Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
            mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
        end

        mult2 = 1;
        for m=1:i - T2
            Sigma = findsigma(T3, T2, i - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end

        Pij = ((Rtotal^T1 * mult1 * mult2) / (factorial(i) * MuH^i)) * P00;
    end
end

if (i == T3)
    if(j == 0)
        mobility1 = Rhd / Rnd;
        mobility2 = Rhv / Rnv;
        mult1 = 1;
        for m=1:T2 - T1
            Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
            mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
        end

        mult2 = 1;
        for m=1:i - T2
            Sigma = findsigma(T3, T2, i - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end
```

```
        Pij = ((Rtotal^T1 * mult1 * mult2) / (factorial(i) * MuH^i)) * P00;
    else
        mult = 1;
        for m=1:j
            mult = mult * (i*MuH + m*MuQ);
        end

        Pi0 = findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, 0, scheme);
        Pij = (Rhd^j / mult) * Pi0;
    end
end

if i >= T3 + 1
    if(j == 0)
        mobility1 = Rhd / Rnd;
        mobility2 = Rhv / Rnv;
        mult1 = 1;
        for m=1:T2 - T1
            Sigma = findsigma(T2, T1, T2 - m, mobility1, scheme);
            mult1 = mult1 * (Sigma * Rnd + Rtotal - Rnd);
        end

        mult2 = 1;
        for m=1:T3 - T2
            Sigma = findsigma(T3, T2, T3 - m, mobility2, scheme);
            mult2 = mult2 * (Sigma * Rnv + Rhd + Rhv);
        end
        Pij = ((Rtotal^T1 * mult1 * mult2 * Rhv^(i-T3)) / (factorial(i) * MuH^i)) * P00;
    else
        mult = 1;
        for m=1:j
            mult = mult * (m*MuQ);
        end

        Pi0 = findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, 0, scheme);
        Pij = (Rhd^j / mult) * Pi0;
    end
end

out = Pij;
```

```
%findpb(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the blocking probability of new voice/data calls
%   for DCRS and GCS

function out = findpb(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
```

```
Pb = [0.0, 0.0];
mobility1 = Rhv/Rnv;
mobility2 = Rhd/Rnd;

for i=T2:T3-1
   Pb(1) = Pb(1) + ((1 - findsigma(T3, T2, i, mobility1, scheme)) * findpij(C, T1, T2,
T3, K, Rhv, Rhd, Rnv, Rnd, i, 0, scheme));
end

for i=T3:C
   for j=0:K
      Pb(1) = Pb(1) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme);
   end
end

for i=T1:T2-1
   Pb(2) = Pb(2) + ((1 - findsigma(T2, T1, i, mobility2, scheme)) * findpij(C, T1, T2,
T3, K, Rhv, Rhd, Rnv, Rnd, i, 0, scheme));
end

for i=T2:T3-1
   Pb(2) = Pb(2) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, 0, scheme);
end

for i=T3:C
   for j = 0:K
      Pb(2) = Pb(2) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme);
   end
end

out = Pb;
```

```
%findpd(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the dropping probability of handoff voice/data
%   calls for DCRS and GCS

function out = findpd(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)

Pd = [0.0, 0.0];
MuQ = 1/4;

for j=0:K
   Pd(1) = Pd(1) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, C, j, scheme);
end
```

```
for i=T3:C
   for j=1:K
      Pd(2) = Pd(2) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme) * j *
MuQ;
   end
end

Pd(2) = Pd(2) / Rhd;

for i=T3:C
   Pd(2) = Pd(2) + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, K, scheme);
end

out = Pd;
```

```
%findu(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the system utlization for DCRS and GCS

function out = findu(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)

sum = 0;

for i=1:T3-1
   sum = sum +  i * findpij(C,T1,T2,T3,K,Rhv, Rhd, Rnv, Rnd,i,0, scheme);
end

for i=T3:C
   for j=0:K
      sum = sum + i * findpij(C,T1,T2,T3,K,Rhv, Rhd, Rnv, Rnd,i,j, scheme);
   end
end

U = sum/C;

out = U;
```

```
%findlq(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the average queue length for DCRS and GCS

function out = findlq(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)

lq = 0.0;

for j=1:K
   for i=T3:C
```

```
      lq = lq + j * findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, j, scheme);
   end
end

out = lq;
```

```
%findtw(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)
%   This function finds the average waiting time of a handoff data call in
%   queue (Q) for DCRS and GCS

function out = findtw(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme)

lq = findlq(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, scheme);
PiK = 0.0;

for i=T3:C
   PiK = PiK + findpij(C, T1, T2, T3, K, Rhv, Rhd, Rnv, Rnd, i, K, scheme);
end

tw = lq/(Rhd*(1 - PiK));

out = tw;
```

```
%fssfindp0(C, Rhv, Rhd, Rnv, Rnd)
%   This function finds the probability all channels are idle for FSS

function out = fssfindp0(C, Rhv, Rhd, Rnv, Rnd)

sum = deal(0);
MuH = 1/180;
Rtotal = Rhv + Rhd + Rnv + Rnd;

for j = 0:C
   term = (Rtotal^j / (factorial(j) * MuH^j));
   sum = sum + term;
end

P0 = sum^-1;

out = P0;
```

```
%fssfindpj(C, Rhv, Rhd, Rnv, Rnd, j)
%   This function finds the steady state probabilities for FSS
```

```
function out = fssfindpj(C, Rhv, Rhd, Rnv, Rnd, j)

MuH = 1/180;
Rtotal = Rhv + Rhd + Rnv + Rnd;
P0 = fssfindp0(C, Rhv, Rhd, Rnv, Rnd);

if j == 0
   Pj = P0;
end

if j >= 1
   if j <= C
      Pj = (Rtotal^j / (factorial(j) * MuH^j)) * P0;
   end
end

out = Pj;
```

```
%fssfindpb(C, Rhv, Rhd, Rnv, Rnd)
%   This function finds the blocking probability of new voice/data calls
%   for FSS

function out = fssfindpb(C, Rhv, Rhd, Rnv, Rnd)

Pb(1, (1:2)) = fssfindpj(C, Rhv, Rhd, Rnv, Rnd, C);

out = Pb;
```

```
%fssfindpd(C, Rhv, Rhd, Rnv, Rnd)
%   This function finds the dropping probability of handoff voice/data
%   calss for FSS

function out = fssfindpd(C, Rhv, Rhd, Rnv, Rnd)

Pd(1, (1:2)) = fssfindpj(C, Rhv, Rhd, Rnv, Rnd, C);

out = Pd;
```

```
%fssfindu(C, Rhv, Rhd, Rnv, Rnd)
%   This function finds the system utlization for FSS

function out = fssfindu(C, Rhv, Rhd, Rnv, Rnd)

sum = 0;
```

```
for j=0:C
   sum = sum + j * fssfindpj(C, Rhv, Rhd, Rnv, Rnd, j);
end

U = sum/C;

out = U;
```

Appendix B: MATLAB Code for Simulation Model

```
function runsim(Rhv, Rhd, Rnv, Rnd, scheme)

SIM_TIME = 2.0e6;                          % Total simulation time
HANDOFF_VOICE_ARR_TIME = 1/Rhv; % Mean time between handoff voice calls
HANDOFF_DATA_ARR_TIME = 1/Rhd;  % Mean time between handoff data calls
NEW_VOICE_ARR_TIME = 1/Rnv;           % Mean time between new voice calls
NEW_DATA_ARR_TIME = 1/Rnd;             % Mean time between new data calls
SERV_TIME = 180.0;                         % Mean service time
DWELL_TIME = 4.0;                          % Mean dwell time
NUM_CHANNELS = 100;                     % Number of channels
NUM_GUARD_CHANNELS = [0, 5, 10, 15]; % [C-C, C-T3, C-T2, C-T1]
Q_SIZE = 1;                                     % Queue size
ARRIVAL = 1;                                   % Event #1 (arrival)
DEPARTURE = 2;                              % Event #2 (departure)
MOBILITY = [Rhv/Rnv, Rhd/Rnd];
Ta = [HANDOFF_VOICE_ARR_TIME, HANDOFF_DATA_ARR_TIME,
NEW_VOICE_ARR_TIME, NEW_DATA_ARR_TIME];
Ts = SERV_TIME;
Tq = DWELL_TIME;
time = 0.0;                                      % Simulation time
t1 = [0.0, 0.0, 0.0, 0.0];                  % Time for next event #1 (arrival) [hv, hd,
                                                      nv, nd]
t2 = java.util.LinkedList;                  % Time for next event #2 (departure)
num_free_channels = NUM_CHANNELS;  % Number of free channels
k = java.util.LinkedList;                    % Number of calls (handoff data) waiting
                                                      in queue
event = ARRIVAL;                             % Arrival/departure
num_system = 0;                               % Number of calls in the system
num_new = [0, 0];                              % Total number of new calls [nv, nd]
num_handoff = [0, 0];                        % Total number of handoff calls [hv, hd]
num_blocked = [0, 0];                        % Total number of blocked calss [nv, nd]
num_dropped = [0, 0];                        % Total number of dropped calss [hv, hd]
num_queued = 0;                               % Total number of queued handoff data
                                                      calls
area_under_s = 0.0;                          % Area of number of customers in the
                                                      system
ts = time;                                         % Variable for "last event time"
num_timedout = 0;                             % Total number of timed out handoff data
                                                      calls
queueing_time = 0.0;                        % Total queueing time

while (time < SIM_TIME)
```

```
if(~t2.isEmpty())
   java.util.Collections.sort(t2);
   if(min(t1) < t2.getFirst())
      event = ARRIVAL;
   else
      event = DEPARTURE;
   end
else
   event = ARRIVAL;
end

if(event == ARRIVAL)
   [~, call_type] = min(t1);
   % Call type, #1 hv #2 hd #3 nv #4 nd
   if(call_type > 2)
      % New call
      time = t1(call_type);
      area_under_s = area_under_s + num_system * (time - ts);
      num_new(call_type - 2) = num_new(call_type - 2) + 1;
      ts = time;
      if(num_free_channels > NUM_GUARD_CHANNELS(call_type))
         num_system = num_system + 1;
         t2.add(time + exprnd(Ts));
         num_free_channels = num_free_channels - 1;
      elseif(num_free_channels > NUM_GUARD_CHANNELS(call_type - 1))
         C = NUM_CHANNELS - NUM_GUARD_CHANNELS(call_type - 1);
         T = NUM_CHANNELS - NUM_GUARD_CHANNELS(call_type);
         i = NUM_CHANNELS - num_free_channels;
         if(binornd(1, findsigma(C, T, i, MOBILITY(call_type - 2), scheme)) == 1)
            num_system = num_system + 1;
            t2.add(time + exprnd(Ts));
            num_free_channels = num_free_channels - 1;
         else
            num_blocked(call_type - 2) = num_blocked(call_type - 2) + 1;
         end
      else
         num_blocked(call_type - 2) = num_blocked(call_type - 2) + 1;
      end
      t1(call_type) = time + exprnd(Ta(call_type));
   else
      % Handoff call
      time = t1(call_type);
      area_under_s = area_under_s + num_system * (time - ts);
      num_handoff(call_type) = num_handoff(call_type) + 1;
      ts = time;

      li = k.listIterator;
```

```
      while (li.hasNext())
         tq = li.next();
         if(tq(2) <= time)
            li.remove();
            num_timedout = num_timedout + 1;
            queueing_time = queueing_time + tq(2) - tq(1);
         end
      end

      if(num_free_channels > NUM_GUARD_CHANNELS(call_type))
         num_system = num_system + 1;
         t2.add(time + exprnd(Ts));
         num_free_channels = num_free_channels - 1;
      elseif((call_type == 2) && (k.size() < Q_SIZE))
         k.addLast([time, time + exprnd(Tq)]);
         num_queued = num_queued + 1;
      else
         num_dropped(call_type) = num_dropped(call_type) + 1;
      end
      t1(call_type) = time + exprnd(Ta(call_type));
   end
else
   % Departure
   time = t2.removeFirst();
   area_under_s = area_under_s + num_system * (time - ts);
   num_system = num_system - 1;
   ts = time;
   num_free_channels = num_free_channels + 1;

   li = k.listIterator;

   while (li.hasNext())
      tq = li.next();
      if(tq(2) <= time)
         li.remove();
         num_timedout = num_timedout + 1;
         queueing_time = queueing_time + tq(2) - tq(1);
      end
   end

   if(~k.isEmpty())
      if(num_free_channels > NUM_GUARD_CHANNELS(2))
         tq = k.getFirst();
         num_free_channels = num_free_channels - 1;
         queueing_time = queueing_time + time - tq(1);
         k.removeFirst();
         t2.add(time + exprnd(Ts));
```

```
            num_system = num_system + 1;
         end
      end
   end
end

display(num_blocked(1)/num_new(1));
display(num_blocked(2)/num_new(2));
display(num_dropped(1)/num_handoff(1));
display((num_dropped(2) + num_timedout )/num_handoff(2));
display((area_under_s/time)/NUM_CHANNELS);
display(queueing_time/(num_handoff(2)-num_dropped(2)));
```