

Prioritized New Call Queuing Policy for Call Admission Control Schemes in Wireless Cellular Networks

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ABSTRACT

This study is composed of two parts. In the first part, an extensive survey on and a classification of call admission control schemes for wireless cellular networks, including discussions on prioritized handoff schemes, mobility models and mobility prediction, are presented. In the second part, a novel prioritized new call queuing mechanism for handoff prioritizing call admission control schemes is introduced. In order to increase the total carried traffic, the proposed approach decreases the blocking probability of new calls by reducing the number of new call connection reattempts. It predicts the time the mobile station will spend in the current cell, and it queues new calls with high predicted remaining time. It is shown through simulations that the proposed scheme outperforms the traditionally employed queuing mechanisms in terms of various parameters. It achieves much lower reattempt and blocking probabilities of new calls without compromising the handoff dropping probability and system utilization.

Keywords: Wireless Cellular Networks, Call Admission Control, Classification, Prioritized New Call Queuing, Reattempt Calls.

ÖZ

Bu çalışma iki bölümden oluşmaktadır. Birinci bölümde, kablosuz ağlarda çağrı kabul denetim sistemleri için, bu sistemlerin sınıflandırılmasını da içeren bir araştırma yer almaktadır. Bu çalışmada öncelikli hücreden hücreye değişim (handoff) yöntemleri, hareketlilik modelleri ve hareket kestimi yöntemleri de tartışılmaktadır. Çalışmanın ikinci bölümünde ise öncelikli hücreden hücreye değişime dayalı yeni çağrı kabul denetimi sistemleri için bir öncelikli yeni çağrı kuyruğu yöntemi önerilmektedir. Bu yöntemde, toplam taşınan trafiği arttırabilmek amacıyla yeni çağrılar için tekrarlanan denemelerin sayısı azaltılarak, yeni çağrıların bloke edilme olasılığı düşürülmektedir. Önerilen yeni yöntem, hareketli cihazın içinde bulunduğu hücrede geçireceği zamanı tahmin ederek, yüksek kestirilmiş kalan zamanı olan çağrıları kuyruğa eklemektedir. Yapılan benzetişim çalışmaları, çeşitli parametreler açısından, önerilen yeni yöntemin geleneksel kuyruk oluşturma yöntemlerinden daha iyi olduğunu göstermektedir. Önerilen yöntem, yeni çağrılar için tekrar deneme ve bloke edilme olasılıklarını önemli oranda düşürürken, sistem verimliliği (utilization) ve hücreden hücreye geçişlerde çağrının sonlanması olailiğinde da geleneksel yöntemlere benzer değerleri korumaktadır.

Anahtar Kelimeler: Kablosuz Hücresel Ağlar, Çağrı Kabul Denetimi, Sınıflama, Öncelikli Yeni Çağrı Kuyruğu Oluşturma, Tekrarlanan Çağrı Deneme.



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TABLE OF CONTENTS

ABSTRACT	iii
ÖZ	iv
ACKNOWLEDGMENTS	vi
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF SYMBOLS/ABBREVIATIONS	xviii
1 INTRODUCTION	1
1.1 Previous work	2
1.2 Contributions of the Thesis	3
1.3 Thesis organization	4
2 BACKGROUND	6
2.1 General concepts on cellular wireless networks	6
2.2 Mobility modeling	9
2.3 Call Admission Control schemes.....	12
3 CALL ADMISSION CONTROL CLASSIFICATION.....	14
3.1 Classification of call admission control schemes based on various parameters	14
3.1.1 The type of traffic used in the schemes.....	16
3.1.2 The type of information used in admission control	17
3.1.3 The way handoff requests are handled.....	17
3.1.3.1 Non-prioritized handoff schemes.....	17
3.1.3.2 Prioritized handoff schemes.....	18

3.2 Classification of prioritized call admission control schemes.....	19
3.2.1 Handoff queuing schemes.....	21
3.2.2 Channel reservation schemes.....	22
3.3 Classification of channel reservation schemes	23
3.3.1 Cell-oriented schemes	23
3.3.1.1 Non-predictive cell-oriented reservation (Guard Channel schemes)	23
3.3.1.2 Predictive cell-oriented reservation	24
3.3.2 Mobile-oriented schemes	25
3.3.2.1 Non-predictive mobile-oriented reservation	25
3.3.2.2 Predictive mobile-oriented reservation	27
3.4 Classification of predictive mobile-oriented channel reservation schemes.....	34
3.4.1 Prediction based on current mobility parameters.....	37
3.4.2 Prediction based on observation histories.....	40
3.4.3 Prediction based on current mobility parameters and observation histories...	43
3.5 Predictive mobile-oriented channel reservation schemes and their characteristics	47
4 PRIORITIZED NEW CALL QUEUING POLICY	50
4.1 Queuing threshold time.....	50
4.2 Remaining time	51
4.3 Flow diagram of the Prioritized New Call Queuing policy	52
5 TRAFFIC MODELS.....	54
5.1 Characteristics of a traffic model.....	54
5.1.1 Call service time.....	54
5.1.2 Cell dwell time	55

5.1.3 New call reattempt time	55
5.1.4 Call arrival process.....	55
5.2 Traffic model of the Prioritized New Call Queuing policy combined with Guard Channels (PNCQ_GC).....	57
5.3 Traffic model of Simple New Call Queuing policy combined with Guard Channels (SNCQ_GC).....	59
6 SIMULATION MODELS	60
6.1 Simulation tool.....	60
6.2 Simulation models	61
6.2.1 Fully Shared Scheme (FSS)	61
6.2.2 Guard Channel scheme with single class of traffic.....	62
6.2.3 Guard Channel scheme with multiple classes of traffic.....	63
6.2.4 Guard Channel scheme with multiple classes of traffic and new call reattempts	65
6.2.5 Simple New Call Queuing policy combined with Guard Channels (SNCQ_GC) and new call reattempts	67
6.2.6 Prioritized New Call Queuing policy combined with Guard Channels (PNCQ_GC) and new call reattempts	69
6.3 Simulation parameters	71
6.4 Performance measures	71
7 SIMULATION RESULTS	73
7.1 Values of the simulation parameters.....	73
7.2 Performance analysis of the PNCQ_GC scheme.....	75
7.2.1 Impact of new call reattempts	75

7.2.2 Impact of the number of reserved handoff channels.....	78
7.2.3 Impact of the queue length.....	81
7.2.4 Impact of the queuing threshold.....	84
7.2.5 Impact of the varying traffic conditions.....	87
7.3 Comparison of PNCQ_GC and SNCQ_GC schemes.....	90
7.3.1 Case 1: $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$	91
7.3.2 Case 2: $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$	93
7.3.3 Case 3: $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$	96
7.3.4 Overview	99
8 CONCLUSION.....	100
REFERENCES	102
APPENDICES	123
APPENDIX A: Accuracy Estimation of the Obtained Results Using Confidence Intervals.....	124
A.1 Confidence intervals.....	124
A.1.1 Confidence interval	124
A.1.2 Confidence limits	124
A.1.3 Confidence level	125
A.1.4 Confidence interval for a mean	125
A.1.5 Calculation of confidence interval	126
A.2 Accuracy estimation of the simulation results	127
APPENDIX B: Verification of the Obtained Results	128
B.1 Fully Shared Scheme.....	128
B.2 Guard Chanel Scheme	130

B.3 Conclusion.....	133
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LIST OF TABLES

Table 3.1: Classification of CAC schemes based on various parameters.....	15
Table 3.2: Classification of prioritized call admission control schemes.....	20
Table 3.3: Classification of predictive mobile-oriented channel reservation schemes...	36
Table 3.4: Characteristics of predictive mobile-oriented channel reservation schemes..	48
Table 6.1: Simulation parameters.....	71
Table 7.1: Values of the simulation parameters.....	75
Table A.1: Results of confidence interval calculations of FSS for CDP with 1 call/second arrival rate.....	122
Table B.1: Verification of results from simulation of FSS with $c = 2$, $I/\mu = 1$	124
Table B.2: Verification of results obtained from simulation of GSC with $C = 2$, $C_h = 1$, $I/\mu = 1$, $\lambda_h = \lambda_n = 0.5\lambda$	127

LIST OF FIGURES

Figure 2.1: Architecture of a cellular network.....	7
Figure 2.2: Handoff	8
Figure 4.1: Illustration of distance from MS to the cell boundary.....	51
Figure 4.2: Flow diagram of the PNCQ policy for mobile users.....	53
Figure 5.1: Traffic model of the PNCQ_GC scheme.....	58
Figure 5.2: Traffic model of the SNCQ_GC scheme.....	59
Figure 6.1: Simulation model of FSS.....	62
Figure 6.2: Simulation model of GC scheme with single class of traffic.....	63
Figure 6.3: Simulation model of GC scheme with multiple classes of traffic.....	64
Figure 6.4: Simulation model of GC scheme with multiple classes of traffic and new call reattempts.....	66
Figure 6.5: Simulation model of SNCQ_GC scheme.....	68
Figure 6.6: Simulation model of PNCQ_GC scheme.....	69
Figure 7.1: CRP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20, h = 4, m = 6, \alpha = 0.3, \beta = 0.5$ and $\delta = 0.8$	76

Figure 7.2: CBP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20, h = 4, m = 6, \alpha = 0.3, \beta = 0.5$ and $\delta = 0.8$	77
Figure 7.3: CDP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20, h = 4, m = 6, \alpha = 0.3, \beta = 0.5$ and $\delta = 0.8$	78
Figure 7.4: Utilization versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20, h = 4, m = 6, \alpha = 0.3, \beta = 0.5$ and $\delta = 0.8$	78
Figure 7.5: CRP versus interarrival time for PNCQ_GC scheme for various h values with $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	79
Figure 7.6: CBP versus interarrival time for PNCQ_GC scheme for various h values with $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	80
Figure 7.7: CDP versus interarrival time for PNCQ_GC scheme for various h values with $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	80
Figure 7.8: Utilization versus interarrival time for PNCQ_GC scheme for various h values with $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	81
Figure 7.9: CRP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20, h = 8, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	82
Figure 7.10: CBP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20, h = 8, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	83
Figure 7.11: CDP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20, h = 8, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	83
Figure 7.12: Utilization versus interarrival time for PNCQ_GC scheme for various m values with $n = 20, h = 8, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$	84

Figure 7.13: CRP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20, h = 8, m = 6, \alpha = 0.3, \gamma = 1.0$ and $\delta = 0.8$	85
Figure 7.14: CBP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20, h = 8, m = 6, \alpha = 0.3, \gamma = 1.0$ and $\delta = 0.8$	86
Figure 7.15: CDP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20, h = 8, m = 6, \alpha = 0.3, \gamma = 1.0$ and $\delta = 0.8$	86
Figure 7.16: Utilization versus interarrival time for PNCQ_GC scheme for various β values with $n = 20, h = 8, m = 6, \alpha = 0.3, \gamma = 1.0$ and $\delta = 0.8$	87
Figure 7.17: CRP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20, h = 8, m = 6, \alpha = 0.3$ and $\gamma = 1.0$	88
Figure 7.18: CBP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20, h = 8, m = 6, \alpha = 0.3$ and $\gamma = 1.0$	89
Figure 7.19: CDP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20, h = 8, m = 6, \alpha = 0.3$ and $\gamma = 1.0$	90
Figure 7.20: Utilization versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20, h = 8, m = 6, \alpha = 0.3$ and $\gamma = 1.0$	90
Figure 7.21: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	91
Figure 7.22: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	92
Figure 7.23: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	92

Figure 7.24: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	93
Figure 7.25: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 1, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	94
Figure 7.26: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 1, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	95
Figure 7.27: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 1, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	95
Figure 7.28: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 1, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$	96
Figure 7.29: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.75$ and $\gamma = 1.0$	97
Figure 7.30: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.75$ and $\gamma = 1.0$	98
Figure 7.31: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.75$ and $\gamma = 1.0$	98
Figure 7.32: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5$ and $\gamma = 1.0$	99
Figure B.1: CBP versus arrival rate for simulation and analytical results of FSS with $c = 2, I/\mu = 1$	124
Figure B.2: CDP versus arrival rate for simulation and analytical results of FSS with $c = 2, I/\mu = 1$	125

Figure B.3: CBP versus arrival rate for simulation and analytical results of GCS with $C = 2$, $C_h = 1$, $I/\mu = 1$, $\lambda_h = \lambda_n = 0.5\lambda$ 127

Figure B.3: CDP versus arrival rate for simulation and analytical results of GCS with $C = 2$, $C_h = 1$, $I/\mu = 1$, $\lambda_h = \lambda_n = 0.5\lambda$ 128



LIST OF SYMBOLS/ABBREVIATIONS

α	Weight of handoff calls
β	Portion of new call arrival rate with $t_b < t_q$
γ	Portion of blocked new calls that try to reestablish a connection
δ	Weight of real-time calls
θ	Direction of mobile station's travel
λ	Gross arrival rate into a cell
λ'	Gross arrival rate including retries
λ_n	New call arrival rate
λ_h	Handoff call arrival rate
λ_{rt}	Arrival rate of real-time calls
λ_{nrt}	Arrival rate of nonreal-time calls
$\lambda_{rt,h}$	Arrival rate of real-time handoff calls
λ_r	Arrival rate of the repeated new calls
$\lambda_{rt,n}$	Arrival rate of real-time new calls
$\lambda_{nrt,h}$	Arrival rate of nonreal-time handoff calls
$1/\mu_s$	Average call service time
$1/\mu_r$	Average new call reattempt time
$1/\mu_d$	Average cell dwell time
A	Area of the cell

ACR	Adaptive Channel Reservation
BS	Base Station
C	Total number of channels
C_a	Number of already allocated channels
CAC	Call Admission Control
CBP	New call blocking probability
CDP	Handoff dropping probability
C_h	Number of channels reserved for handoff calls
CP	Complete Partitioning
C_r	Number of channels required for each call
CRP	Call reattempt probability
CS	Complete Sharing
CVP	Cell Visiting Probability
d	Distance between the mobile station and the cell boundary
DCA	Dynamic Channel Allocation
$E[T_d]$	Average cell dwell time
$E[T_r]$	Average new call reattempt time
$E[v]$	Mean of speed v
$E[V_f]$	Average speed of fast MSs
$E[V_s]$	Average speed of slow MSs
ETD	Expected Travel Distance
FIFO	First-In-First-Out

FSS	Fully Shared Scheme
GC	Guard channel
GPS	Global Positioning System
GPSS	General Purpose Simulation System
h	Number of reserved channels for handoff calls
HLP	Hierarchical Location-Prediction
HO	Handoff calls
k	Number of channels available to new calls
L	Length of a cell perimeter
m	Queue length
MLCT	Most Likely Cell-Time
MMP	Mobile Motion Prediction
MNN	Multilayer Neural Network
MPA	Motion Prediction Algorithm
k	Number of channels available to new calls
L	Length of a cell perimeter
m	Queue length
MPP	Mobility Pattern Profile
MS	Mobile station
MSC	Mobile Switching Center
n	Maximum number of retries
N_b	Total number of blocked (rejected) new calls
NC	New calls

NC_{nq}	New calls with $t_b < t_q$
NC_q	New calls with $t_b \geq t_q$
N_d	Total number of dropped (rejected) handoff calls
N_{ho}	Total number of handoff calls
N_{ncr}	Total number of new calls including connection reattempts
N_r	Total number of new call retries
N_{ret}	Total number of retries
PCR	Predictive Channel Reservation
PMOCR	Predictive mobile-oriented channel reservation
PNCQ_GC	Prioritized New Call Queuing policy combined with Guard Channels
PSS	Pilot Signal Strength
PSTN	Public Switched Telephone Network
QoS	Quality of Service
r	Distance from the base station to mobile station
R	Radius of the cell
RPD	Regularity-Pattern Detection
RSS	Received Signal Strength
RSSI	Received Signal Strength Indication
RTW	Reservation Time Window
RWP	Random Waypoint
SC	Shadow Cluster

SiS-HoP	Simple and Scalable Handoff Prioritization
SMD	Speed and Moving Direction
SNCQ	Simple New Call Queuing
SNCQ_GC	Simple New Call Queuing policy combined with Guard Channels
SPPQ	Signal Prediction Priority Queuing
SSMC	Signal Strength for Multimedia Communication Scheme
t_b	Time within which the MS will reach the boundary of its current cell
TMP	Threshold of Mobility Probability
t_q	Queuing threshold time
U	Utilization
v	Speed of the mobile station

Chapter 1

INTRODUCTION

In wireless cellular networks, dropping an ongoing connection while changing cells (handoff) is generally considered to have a more negative impact from users' perception than rejecting (blocking) a newly requested connection. Therefore, Call Admission Control (CAC) schemes give higher priority to handoff calls than new calls by either reserving channels exclusively for handoff calls (channel reservation schemes) or by allowing handoff calls to be queued (handoff queuing schemes) [1]. Some CAC schemes combine both techniques. All CAC schemes that give higher priority to handoff calls have a common characteristic: ensuring a lower Call Dropping Probability (CDP) of handoff calls. CDP is the probability of a handoff connection being forcibly terminated due to a lack of resources in the target cell, at the expense of an increased new Call Blocking Probability (CBP). CBP is the possibility of a new connection request to be rejected admission into the network. This situation may be improved by allowing the queuing of new calls, as new calls are not very sensitive to delay [29]. The presence of the new call queue does not affect the priority of the handoffs in the system [106].

1.1 Previous work

Mostly, handoff prioritizing CAC schemes employ a simple First-In-First-Out (FIFO) queuing policy which basically queues all the new calls. We refer to it as the Simple New Call Queuing (SNCQ) policy. It is usually combined with the well-known Guard Channel (GC) scheme [22], also known as the Cutoff Priority scheme. Such schemes reserve a fixed number of channels exclusively for handoff calls in each cell. The review of some important schemes combining SNCQ policy and GC scheme follows.

In [107], Guerin analyzed a system which combines an infinite new call queue with the GC scheme. The performance analysis by Guerin showed that with this system, the CDP decreases much faster than the increase in the probability of delay for new calls.

A hierarchical cellular system with guard channels and finite queues for both new and handoff calls is analyzed in [108]. The authors investigated the effect of the waiting time in the queue on the new and handoff calls and the effect of buffer sizes and guard channel numbers on the performance of the macrocell and microcells. The effect of the withdrawal (reneging) of new calls from the queue because of the callers' impatience was also examined. Their results showed that the provision of the queuing scheme and GC scheme can effectively reduce the CBPs and CDPs.

In [106], Lau and Maric presented an analytical model that considers the effects of handoffs of queued new call requests, with a finite queue length, which is used to study the effect of the mobility of queued new call requests. It was found that the mobility of the queued new call requests reduces the average queuing delay, but it increases CBP in general.

The channel borrowing scheme with finite handoff and new call queues and guard channels is explored in [109], which provides a design mechanism for the formal system parameters of the number of guard channels, the handoff queue length and the new call queue length for the system. The simulation results showed that the performance of the system with channel borrowing is much better than the system without channel borrowing.

In [110], McMillan analyzed a GC scheme combined with separate queues for new and handoff calls. He provided an analysis of the systems with finite and infinite new call queues. It is assumed that the new call traffic may only be delayed for service up to a fixed timeout, after which, the traffic is lost. The results showed that queuing of new call attempts governed by a fixed timeout can be reasonably efficient in improving channel utilization.

1.2 Contributions of the Thesis

The first contribution of this thesis is a broad survey and a novel classification of Call Admission Control (CAC) schemes in wireless cellular networks, which includes a review of work done in the field of handoff prioritization and user mobility prediction. The classification of Call Admission Control schemes is based on the classification of Handoff Channel Allocation (HOCA) schemes presented in [1] and [118]. In [118], some of the popular HOCA schemes were investigated and their behaviors were simulated. These schemes were evaluated and compared in terms of call blocking probability, call dropping probability and system utilization.

The second contribution is a Prioritized New Call Queuing (PNCQ) policy [120], which, as opposed to the existing new call queuing schemes, does not simply queue all the new calls, but it prioritizes new calls with high remaining time (the time the mobile station (MS) is expected to spend in the current cell), by queuing them in an exclusive queue. Our scheme takes into consideration the fact that in real-life networks, new calls tend to reestablish a connection after a certain period of time [111]-[114]. The connection reattempts are known to create a negative impact on the system performance [111]-[114]. The PNCQ approach tries to reduce the number of new call connection reattempts by queuing the new calls with high remaining time as they will generate more reattempts than calls with low remaining time. The PNCQ mechanism can be integrated with any handoff prioritizing CAC scheme. To evaluate the performance of the PNCQ policy, we combined it with the GC scheme (PNCQ_GC) and compared its performance with the GS scheme employing SNCQ approach (SNCQ_GC) [107], [108], [110]. The simulation results show that the PNCQ_GC scheme outperforms the SNCQ_GC scheme in terms of different parameters and under various conditions.

1.3 Thesis organization

The following is a short summary of the remainder of this dissertation.

Chapter 2 provides background information, which includes a discussion on general concepts of cellular wireless networks, review of the work done in the area of mobility modeling, and an overview of Call Admission Control (CAC) schemes.

In Chapter 3, we present a classification of Call Admission Control (CAC) schemes and detailed assessment of the work done in this field of handoff prioritization and mobility prediction.

The Prioritized New Call Queuing (PNCQ) policy is introduced in Chapter 4.

Chapter 5 contains the traffic models of the Prioritized New Call Queuing policy combined with Guard Channels (PNCQ_GC) and the Simple New Call Queuing policy combined with Guard Channels (SNCQ_GC).

The simulation tool used for our simulations, performance measures, simulation models and parameters are discussed in Chapter 6.

In Chapter 7, we present the performance analysis of PNCQ_GC scheme and performance comparison of PNCQ_GC and SNCQ_GC schemes.

Finally, Chapter 8 contains some conclusions and suggestions of areas for further study.

Chapter 2

BACKGROUND

This chapter provides the background information for this thesis. It is organized as follows. Section 2.1 discusses the underlying concepts of cellular wireless networks. A survey of the work done in the area of mobility modeling is presented in Section 2.2. Finally, Section 2.3 offers a brief introduction to CAC schemes.

2.1 General concepts on cellular wireless networks

In general, cellular wireless networks consist of three key elements: the *mobile station* (MS), the *base station* (BS), and the *mobile switching center* (MSC). The MS may be any handheld device, such as a mobile phone or a portable computer.

The region covered by each BS is known as its *cell*. BSs are connected to each other and to a MSC. The MSC acts as a gateway from the cellular network to other networks, such as the Internet, or the Public Switched Telephone Network (PSTN). Each MS communicates via the specific BS of the cell it is currently residing in. Figure 2.1 shows the architecture of a cellular network.

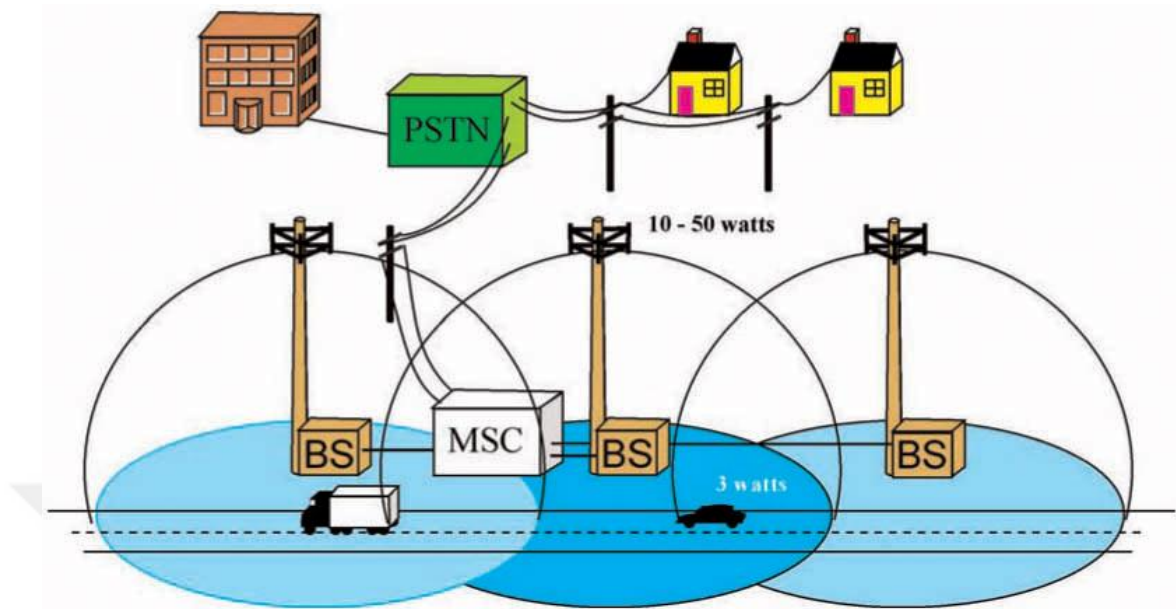


Figure 2.1: Architecture of a cellular network [123].

A wireless cellular communication system should be able to provide continuous service when its users are mobile. The *Handoff* (or handover) process is used to achieve this goal when a user is moving from one cell to another (refer to Figure 2.2). Handoff is a process of changing the channel (the frequency, the time slot, the spreading code, or a combination of them) associated with the current connection while a call is in progress [38].

The size and shape of each cell in a network depends on the nature of the terrain in the region, the number of base stations, and the transmit/receive range of each base station. In theory, the cells in a network overlap, and a MS can be within range of more than one base station. When two cells overlap, an imaginary handoff boundary is assumed along the common chord.

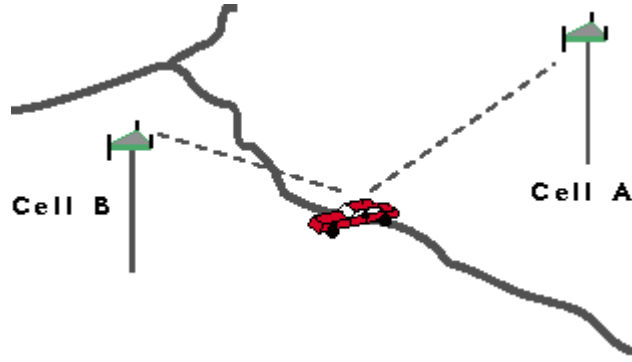


Figure 2.2: Handoff [124].

In the ideal case, when the radii of all neighboring cells are assumed to be the same, the shape of each cell, formed by the imaginary handoff boundary lines, is a perfect hexagon. In reality, the radius of a cell varies in different directions due to the terrain, co-channel interference effects, and noise [62].

The handoff procedure can be summarized as follows. When a MS moves away from its BS-A towards a new BS-B, the Received Signal Strength (RSS) from this MS viewed by BS-A decreases, while the RSS viewed by BS-B increases. A handoff request is sent to BS-B (the target BS) when the MS M enters the handoff area C (overlapping area of two cells). The handoff area is defined as the area in which the average RSS of a MS receiver from the BS is between the handoff threshold level and the receiver threshold level. The handoff threshold is set at the point where the power received from the BS of a neighboring cell has started to exceed the power received from the current BS by a certain amount and/or for a certain time, while the receiver threshold is the point at which the received power from the BS is at the minimum acceptable level [65]. The target BS will handle the handoff request while MS is in the handoff area. If the target

BS cannot find enough available bandwidth for allocating to the MS, the handoff call is dropped (forced to terminate). The Call Dropping Probability (CDP) is defined as the probability of a handoff connection being forcibly terminated due to a lack of resources in the target cell.

When a new connection is denied access into the network it is said to be *blocked*. The Call Blocking Probability (CBP) is defined as the probability of a new connection request being rejected for admission into the network.

Both CBP and CDP are fundamental Quality of Service (QoS) parameters in cellular wireless networks. They offer a good indication of a network's QoS with regards to mobility. Another important QoS parameter is the bandwidth (channel) utilization. It is a degree to which the network makes an effective use of its bandwidth.

2.2 Mobility modeling

Mobility modeling plays an important role in the performance analysis of a cellular wireless network. A mobility model is designed to describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time [115]. The commonly used models are the random walk, Random Waypoint (RWP), fluid flow, Markovian and activity-based mobility models.

The simplest of these models is the random walk model. It was originally proposed to emulate the unpredictable movement of particles in physics. Also referred as the *Brownian Motion* [96], it is employed to model the movements of users in a cellular network. It assumes that the direction of each user-movement is completely random, and hence each neighboring cell may be visited with equal probability. This model is easy to

implement as it requires no state information to predict the next cell to be visited by a user. However, due to its simplicity, this model may lead to inaccurate predictions [97].

The random waypoint (RWP) model was first proposed by Johnson and Maltz [98]. In the RWP model, the nodes, i.e. mobile users, move along a zigzag path, consisting of straight legs from one waypoint to the next. Each waypoint is assumed to be drawn from the uniform distribution over the given convex domain. The RWP model became a 'benchmark' mobility model to evaluate the mobile ad-hoc network routing protocols due to its simplicity and wide availability [96]. In [99], the RWP model is studied in the context of cellular networks.

A very general method, ignoring individual users but considering the network as a whole, is called the fluid-flow method. This method aggregates the movement patterns of users, and consequently can help optimize the network's utilization and design at a macroscopic level. However, fluid-flow provides no insight on a smaller scale, nor will it give any predictions as to specific user movements for any specific user [97].

In Markovian mobility models, future user movements are predicted by looking at the past movements (i.e., the history). Therefore, the past movements must be kept, and at large computational cost, every inter-cell movement probability is defined for each user [97].

The activity-based model is an extension of the Markovian model. In this model, parameters such as time of day, current location, and predicted destination are also stored and evaluated to create future movement probabilities [97]. Such models are computationally complex and require a large set of input data.

Looking at mobility analysis from a different perspective, movement patterns of the MS have to be characterized in order to evaluate the performance of the system. In cellular networks, mobility patterns can be investigated by:

- a) the analytical method with mathematical formulation,
- b) by measuring the geographic position, or
- c) by exploring trace data [89].

For instance, M. M. Zonoozi and P. Dassanayake [90] analytically investigate mobility patterns using mathematical formulation. Their model is used to characterize different mobility related traffic parameters in cellular mobile communication systems. These parameters include the distribution of the cell residence time of both new and handover calls, the channel holding time, and the average number of handovers per call. Their results show that the generalized gamma distribution is sufficient to describe cell residence time distribution of both new and handover calls, and the negative exponential distribution is a good estimate for channel holding time distribution. It is also shown that an increase in mobile drift in a cell can be treated as contributing to an effective increase in the cell radius and the increase in speed of the mobile in a cell can be assumed as contributing to a decrease in the cell size, and vice versa.

In [91], geographic positions are measured to determine the tele-traffic characteristics. The data bank comes from position information of taxi movements in large and small cities using Global Positioning System (GPS) receivers fixed on taxis. The results show that the difference in the handover rate and the CDP between large and small cities is small.

Ref. [92] provides an investigation into mobility by measuring the geographic position of the MS. The geographic positions are measured from different types of

vehicles with GPS receivers. Overlaying the cells, cell cross-over rate, and cell dwell time are determined. Cell cross-over time changes with a change in the vehicle type, but this change is inversely proportional to the cell size. In order to get the handoff rate and cell dwell time for the communication terminals, the communication holding time is considered and a method similar to [93] is applied. When cells are small, the cell dwell time during communications mostly depends on the motion of the vehicle, whereas it depends on the holding time distribution otherwise.

2.3 Call Admission Control schemes

Call Admission Control (CAC) refers to the task of deciding whether or not a certain connection request will be admitted into, and supported by, the network. It is well known that, from the end-user's perspective, it is far less acceptable to have a call dropped than blocked. Therefore, the main objective of CAC schemes in cellular wireless networks is to minimize the CDP. On the other hand, maximizing the income by improving the bandwidth utilization is the main aim of network service providers. Hence, a scheme becomes more efficient by allowing a high utilization of the wireless bandwidth (by accommodating a higher number of new calls) while guaranteeing the QoS of handoff calls.

CAC schemes should take into consideration the different characteristics and QoS requirements for various services and have to be service-dependent. Services in cellular wireless networks can be divided into two types: real-time services (voice service, video-phone, video on demand etc.) and non-real-time services (e-mail, fax, data on demand, file transfer etc.). Real-time services require a guaranteed bounded delay and are very sensitive to interruptions. Non-real-time services usually do not impose tight

delay constraints and transmission delay impacts on performance are usually at an acceptable level. Hence, in CAC schemes, real-time traffic should be given higher priority over non-real-time traffic.

Schemes differentiating between real-time and non-real-time services assume that there is a handoff area for real-time service users but there is no handoff area for non-real-time service users. Instead, the cell boundary is used, which is defined by the points where the RSS of two adjacent cells is equal. When a moving real-time service user holding a channel approaches from a neighboring cell toward the reference cell, if the RSS goes below the handoff threshold of the neighboring cell, a handoff request is generated in the reference cell. When a non-real-time service mobile user holding a channel approaches the reference cell and crosses the cell boundary, a non-real-time service handoff request is generated.

Chapter 3

CALL ADMISSION CONTROL CLASSIFICATION

This chapter presents an extensive survey and a novel classification of CAC schemes. There is no other such classification study that has been published, to the best of our knowledge. Thus, the classification provided here is significant.

This chapter is organized as follows. Section 3.1 contains a classification of CAC schemes based on various parameters. A classification of prioritized CAC schemes is discussed in Section 3.2. Section 3.3 offers a classification of channel reservation schemes, while the classification of predictive mobile-oriented channel reservation schemes is presented in Section 3.4. Lastly, Section 3.5 gives an overview of predictive mobile-oriented channel reservation schemes and their characteristics.

3.1 Classification of call admission control schemes based on various parameters

The following subsections contain classifications of CAC schemes based on the traffic/information type, number of cells involved in the call admission and handling mechanism of handover (HO) requests. Table 3.1 gives a summary of the classifications.

Table 3.1: Classification of call admission control schemes based on various parameters.

Classes		Comments	References
Traffic type	Homogeneous	Each type of traffic is assumed to have the same bandwidth requirements.	[2], [12], [22], [23], [48], [49], [66]
	Multimedia	Each type of traffic has different bandwidth requirements.	[11], [18]-[20], [24]-[26], [35], [38], [39], [50], [51], [53], [70], [71]
Information type	Local	Employ local information in admission control.	[74]
	Remote	Employ remote information in admission control.	[37]
	Local and remote	Employ local and remote information in admission control.	[48], [50]
Number of cells involved in call admission	Cell-oriented	Call admission is performed only in a local cell.	[25], [35]
	Distributed	Call admission is performed in a number of cells.	[10], [20], [37], [48], [50]
Handling mechanism of HO requests	Non-prioritized	Do not differentiate between new and handoff calls.	[2], [21], [30]-[33], [56]
	Prioritized	Give higher priority to handoff calls over new calls.	[3], [9], [12]-[17], [22]-[28], [35]-[41], [45]-[50], [52], [55], [62], [66], [73]

3.1.1 The type of traffic used in the schemes

Based on the type of traffic used, CAC schemes can be categorized into schemes dealing with *homogeneous traffic* (non multimedia traffic) and schemes dealing with *multimedia traffic*. In schemes with homogeneous traffic, each type of traffic is assumed to have the same bandwidth requirements, while in schemes with multimedia traffic, each type of traffic has different bandwidth requirements [1]. Schemes considering homogeneous traffic are not suitable for present and future wireless networks as they do not provide suitable support for multimedia applications.

There are two types of schemes dealing with homogeneous traffic; schemes which consider only one class of traffic, namely, voice, considered in [22], [48], [49], [66], and schemes which consider multiple classes of traffic with the same bandwidth requirements. Two classes of traffic were considered in [2] and [23], in which the classes are based on the speed of the mobile users – high mobility versus low mobility [2], or vehicular call versus portable call [23].

Different types of traffic are considered in multimedia-based schemes – real-time versus non real-time [11], [18], [25], [35], [28], [50], [70] narrowband versus wideband [19] and [20], premium service versus assured service [71], voice versus data [39], voice versus data and video [53], voice versus text, audio, and video [26], voice versus interactive video, videophone, www and e-mail [24]. Some schemes dealing with multimedia traffic give higher priority to a specific call based on its class of traffic, for example, real-time over non real-time [11], [18], [25], [35], [38], [50], [70] and voice over data [51]. In some schemes, a call with higher priority can preempt the operation of calls with lower priority [38], [51].

3.1.2 The type of information used in admission control

CAC schemes can be classified into schemes that consider local information (the amount of unused bandwidth in the cell where the user currently resides) [74], remote information (the amount of unused bandwidth in the neighboring cells) [37] or local and remote information, to determine whether to accept or reject a connection [48]. Since a MS is free to move anywhere, a CAC scheme that relies solely on local information cannot guarantee the QoS requirements of a connection throughout its lifetime [50].

3.1.3 The way handoff requests are handled

Based on the way a handoff request is handled, CAC schemes can be classified into schemes that prioritize or do not prioritize handoff requests. Prioritized CAC schemes restrict the number of new calls accepted to decrease the CDP. They allocate channels to handoff requests more readily compared to new calls. On the other hand, non-prioritized schemes do not differentiate handoff calls from new calls, thus the strict requirements of CDP cannot be met by them.

3.1.3.1 Non-prioritized handoff schemes

Non-prioritized schemes treat handoff calls and new calls equally. In such schemes, the CDP is equal to the CBP. This is very problematic from the user's QoS perspective, since a user would prefer to be refused admission into the system than to be dropped in the middle of service. These schemes perform well in terms of CBP compared to the schemes that prioritize handoffs. Some popular non-prioritized schemes are discussed below.

The Fully Shared Scheme (FSS) [56], [30] is a scheme dealing with single class of traffic. In this scheme, all available channels in the BS are shared by handoff and new calls. Although this results in high channel utilization, it also generates a high CDP.

The Complete Sharing (CS) [31]-[33] policy allows all users equal access to the channels available at all times. This scheme is similar to FSS except that the CS scheme deals with multiple classes of traffic with same or different bandwidth requirements. Like FSS, CS performs well in terms of channel utilization, but weakly in terms of CDP.

The Complete Partitioning (CP) policy divides up the available bandwidth into separate sub-pools according to the user type [31]-[33]. This policy allows for more control of the relative blocking/dropping probabilities at the expense of overall usage of the network. This approach could lead to wasted capacity if the load offered by a traffic stream drops below its allocated capacity [19].

CP schemes can be classified into schemes with dynamic (movable) partition boundaries [2] and schemes with static partition boundaries [31]-[33].

In [21], Haung et al. proposed a hybrid scheme which is a combination of a CP scheme with dynamic boundaries and a CS scheme. The available bandwidth of each cell is partitioned into designated voice channels, designated data channels, and shared channels. Designated voice and data channels are dedicated for voice and data traffic transmissions respectively, while the shared channels can be used by either type of traffic. Voice traffic is blocked from the system if legitimate channels are all in use upon arrival. On the contrary, if legitimate channels are busy, data traffic would be queued in a buffer. The boundary between compartments is dynamically moved in order to efficiently adjust the bandwidth.

3.1.3.2 Prioritized handoff schemes

Prioritized CAC schemes prioritize handoff calls over the new calls. Such schemes have a significant impact on CDP and CBP. All handoff prioritizing schemes have a common characteristic: ensuring a lower CDP at the expense of an increased CBP.

Efficient schemes allow a high utilization of the bandwidth (by accommodating a higher number of new calls) while guaranteeing the QoS of handoff calls. Classification of prioritized CAC schemes is discussed in Section 3.2.

3.2 Classification of prioritized call admission control schemes

Two common ways to prioritize handoff calls over new calls are by reserving channels exclusively for handoff calls and by allowing handoff calls to be queued. Some schemes combine both of these techniques [22]. See Table 3.2 for a classification of prioritized CAC schemes.

Table 3.2: Classification of prioritized call admission control schemes.

Classes			Comments	References
HO Queuing	Non-prioritized		Employ FIFO queuing. Do not prioritize one handoff call over another.	[22]
	Prioritized		Employ prioritized queuing. Prioritize handoffs calls waiting in the queue by reordering them based on various parameters.	[9], [17], [66]
Channel Reservation	Cell-oriented	Non-predictive	Prioritize handoffs by reserving a number of channels exclusively for handoffs in each cell.	[22], [40], [52]
		Predictive	Pre-reserve bandwidth between neighboring cells based on the outcome of the mobility prediction of the cell.	[16]
	Mobile-oriented	Non-predictive	Reserve bandwidth for each MS in a number of cells without determining its future path.	[37], [50]
		Predictive	Reserve bandwidth for each MS based on its predicted path.	[3], [12], [13], [15], [24], [27], [36], [45], [46], [55], [62], [73]

3.2.1 Handoff queuing schemes

In schemes employing queuing for handoff prioritization, handoff calls are not dropped if the target BS is busy, instead, they are delayed in a waiting queue. In such schemes, CDP is decreased at the expense of increased CBP and a decreased ratio of carried-to-admitted traffic because channels are not assigned to new calls until handoff requests in the queue are served. Queuing of handoff requests is possible because of the existence of a time interval that the MS spends between the handoff and the receiver thresholds. When the RSS of the BS in the current cell reaches the handoff threshold, the call is queued to be serviced by a neighbor cell (if queue is not full). The call remains queued until either an available channel in the new neighbor cell is found, or the power level received by the BS in the current cell drops below the receiver threshold. If the call reaches the receiver threshold and a new channel has not been found, the handoff call is dropped.

Handoff queuing techniques can be classified into prioritized and non-prioritized, based on the way handoff calls are handled in the queue. Non-prioritized schemes do not prioritize one call over another; hence, all calls are served in FIFO manner. Prioritized schemes prioritize handoffs calls waiting in the queue by reordering them based on various parameters such as RSS, change in RSS (ΔRSS), traffic type, or a combination of these.

The Guard Channel scheme proposed by Hong and Rappaport in [22] employs a FIFO queuing technique. If the power level received from the source cell's BS falls below the receiver threshold level before the MS is assigned a channel in the target cell, the call is dropped. When a channel is released in the cell, it is assigned to the first handoff call attempt waiting in the queue (if any). If more than one handoff call attempt

is waiting in the queue, the FIFO queuing discipline is used. It is assumed that the queue size at the BS is unlimited - which is not realistic. This scheme is discussed in detail in Section 3.3.1.1.

Tekinay and Jabbari [66] presented a measurement-based prioritization scheme (MBPS) to employ a dynamic priority queuing discipline instead of FIFO. A handoff request is ranked according to how close the MS stands, and possibly how fast it is approaching the receiver level. Since the radio measurements are already made, there is no additional complexity in the employment of this scheme. This scheme offers a better performance in terms of quality of service and spectrum efficiency compared to the FIFO scheme.

Ebersman and Tonguz [17] proposed a signal prediction priority queuing (SPPQ) scheme to improve the MBPS algorithm by using both RSS and Δ RSS, to determine the priority ordering in the handoff queue. They show that even under non-ideal conditions, SPPQ performs better than FIFO and MBPS algorithms.

In [9], the SPPQ algorithm [17] discussed above is extended to handle the multimedia traffic and a new scheme called the Signal Strength for Multimedia Communication Scheme (SSMC) is proposed. In SSMC, if all channels of a BS are occupied, the new call requests within that cell are simply blocked and the handoff requests to that cell are queued. The queued requests are ordered according to a priority value which is based on RSS, Δ RSS and traffic type.

3.2.2 Channel reservation schemes

The main idea behind channel reservation schemes is to prioritize handoff calls by exclusively reserving channels (bandwidth) for them. However, an over-reservation can result in the underutilization of the bandwidth, which is undesirable for service

providers. On the other hand, an under-reservation may result in high CDP, which is undesirable from the users' perspective. Therefore, an efficient channel reservation scheme must accurately estimate the amount of bandwidth (number of channels) to be reserved for handoff users. Section 3.3 contains a classification of channel reservation schemes.

3.3 Classification of channel reservation schemes

Channel reservation schemes can be categorized into cell-oriented and mobile-oriented schemes. The following subsections present the classifications of cell-oriented and mobile-oriented channel reservation schemes.

3.3.1 Cell-oriented schemes

Cell-oriented schemes are based on the behavior of a cell in general; they do not concentrate on the behavior of an individual mobile user in the reservation process. Some non-predictive and predictive cell-oriented schemes are discussed below.

3.3.1.1 Non-predictive cell-oriented reservation (Guard Channel schemes)

Guard channel (GC) schemes, also known as Cutoff Priority schemes, prioritize handoffs by reserving a number of channels exclusively for handoffs in each cell. The main drawback of such schemes is a reduction in the total traffic carried, since fewer channels are assigned to new calls which can be, to some extent, eliminated by allowing the queuing of new calls [29]. Non-predictive schemes are simple as they do not require control information to be exchanged among BSs. However, they are not flexible to varying traffic loads.

In [22], Hong and Rappaport introduced a GC scheme dealing with voice calls. They presented a traffic model and analyzed cellular mobile telephone systems with

handoff. In their work, three mobile schemes for call traffic handling were considered. One of these schemes is non-prioritized and two are prioritized. In the non-prioritized scheme, the BSs make no distinction between new call attempts and handoff attempts. Attempts that find all channels occupied are cleared. In the first priority scheme considered, a fixed number of channels in each cell are reserved exclusively for handoff calls. The second priority scheme employs a similar channel assignment strategy, but, additionally, the queuing of handoff attempts is allowed.

Rappaport and Purzynski [52] extended the work done in [22] to multiple services and platform types. They analyzed the performance based on their proposed mathematical model, with the assumption of stationary traffic.

A GC scheme with multiple thresholds was proposed in [40]. It extends the simple cutoff priority scheme for single stream traffic into multiple classes of traffic. This scheme, in which each type of traffic has its own cutoff threshold, is referred to as the Hybrid Cutoff Priority Scheme. The main characteristic of the scheme is that it supports any number of classes of traffic, each of which can have its own QoS requirements in terms of number of channels needed, length of the connections and the cutoff priority employed. This scheme adopts finite buffering for both new calls and handoff calls. The departure of new calls due to the caller's unwillingness to wait, and the dropping of the queued handoff calls due to unavailability of channels during the handoff period are taken into consideration.

3.3.1.2 Predictive cell-oriented reservation

Predictive cell-oriented reservation schemes pre-reserve channels between neighboring cells based on the outcome of the mobility prediction of the cell. Such

schemes are more flexible to varying traffic loads than non-predictive schemes. However, they are usually not very efficient.

In [16], a scheme named Simple and Scalable Handoff Prioritization scheme (SiS-HoP) was proposed. It consists of an aggregated mobility prediction and handoff channel reservation components. Mobility prediction is based on a small mobility cache, which stores the history of handoffs in each BS. The mobility prediction component does not consider individual MSs. Aggregated handoff probabilities are calculated for each neighboring cell. Using the outcome of the prediction, the channel reservation component calculates the necessary number of channels to be reserved in each neighboring cell and announces results to the neighboring cells. The number of reserved channels in the current cell is adjusted based on handoff reservation requests from the neighboring cells. Despite the scheme's scalability advocated by the authors, it can be ineffective in avoiding handoff droppings depending on the reservation periodicity [105].

3.3.2 Mobile-oriented schemes

Unlike cell-oriented schemes, mobile-oriented schemes are based on the behavior of an individual MS. In such schemes, channel reservation is performed for each MS separately. Non-predictive and predictive mobile-oriented schemes are discussed below.

3.3.2.1 Non-predictive mobile-oriented reservation

Non-predictive mobile-oriented schemes reserve bandwidth for each MS in a number of cells without determining its future path [37], [50]. Such schemes are more adaptable to various network load conditions than GC schemes. On the other hand, they frequently suffer from low bandwidth utilization and high communicational overhead.

In [50], the bandwidth is allocated in the cell where a connection request originates and bandwidth is reserved in all neighboring cells. When a user moves to a new cell, which requires a handoff, the bandwidth reserved in target cell is used to support the handoff connection. In addition, every time a user moves to a new cell, required bandwidth is reserved in the new neighboring cells, and the bandwidth reserved in the cells which are no longer neighbors to the new cell is released.

This scheme distinguishes real-time traffic and non real-time traffic, and if necessary, reduces the bandwidth assigned to non real-time connections to provide higher quality of service to real-time connections. It can also adjust the amount of reserved bandwidth based on the current network conditions. This is done by measuring the average CDP and the reserved bandwidth usage (i.e., how much of the reserved bandwidth is actually being used) and adjusting the amount of reserved bandwidth accordingly, and therefore, it adapts to various network load conditions. However, this scheme wastes resources by reserving bandwidth for portable MSs, which never move, and for moving MSs by reserving bandwidth in all neighboring cells, even though the MS eventually hands off to only one of them.

In [37], Levine *et al.* proposed a distributed CAC scheme which introduced the concept of a Shadow Cluster (SC) – a set of cells the MS might visit in the near future. A shadow cluster defines the “region of influence” of an active MS. The potential influence of the active MS on the channel resources of each cell in the cluster is probabilistically determined by the BS of the current cell, based on previous knowledge of the mobility pattern of the active MS. The area of influence moves along with the MS, when a MS is handed off to another cell. The BS of the cell to which MS has handed off must supply necessary information to the BSs in the new shadow cluster.

Any entries corresponding to the active MS must be deleted from the BSs that formed an old shadow cluster and reserved resources must be freed.

This scheme partitions time into predefined intervals and verifies the feasibility of supporting calls in a shadow cluster over those intervals. Bandwidth estimates are calculated at the beginning of each time interval and the admission decisions are made at the end of each time interval. One of the drawbacks of this scheme is that the admission of new calls is delayed for at least a time period equal to the length of the predefined time intervals [3]. Moreover, communication of large number of messages is required between BSs during every time interval, which can cause a significant overhead in wireless networks. Another shortcoming of the distributed CAC scheme is that it does not provide a way for determining a shadow cluster in real networks, since it assumes either precise knowledge of the previous user mobility or totally random user movements [76].

3.3.2.2 Predictive mobile-oriented reservation

Predictive mobile-oriented channel reservation (PMOCR) schemes perform channel reservation for mobile users based on mobility prediction. Mobility prediction of users is integrated with channel reservation because the best tradeoff between CBP and CDP can only be achieved if for every MS, we know its path and its arrival/departure times in each cell in advance. Since, such a scenario is unrealistic, the next best option is to predict the mobility of the user and determine the cell(s) the user will most likely visit in the near future. Reservation can then be done only in those cells [62].

Unlike non-predictive schemes, predictive schemes reserve bandwidth for each MS based on its predicted path. They reserve bandwidth at the "potential next cell" or a set

of cells an active MS may visit during its lifetime. PMOCR schemes are the most flexible to varying traffic loads. However, they usually suffer from scalability issues, high computation and/or implementation complexity, signaling overhead and unrealistic assumptions.

The reservation in PMOCR schemes is performed before the arrival of the MS, based on its future path, which is predicted using user mobility prediction techniques. Thus, user mobility prediction is a vital component of PMOCR schemes. Many prediction mechanisms have been proposed in the literature, each trying to solve a specific type of problem. Actually, all of these mechanisms are interrelated and many of them can be used in situations other than the ones they are proposed for.

PMOCR schemes incorporate user mobility prediction and bandwidth reservation. On the other hand, there are some schemes which only try to predict the future path of MS, without reserving resources for handoff calls. Such schemes can be employed by channel reservation schemes to predict the user mobility. We will refer to them as “user mobility prediction schemes”. The majority of the user mobility prediction schemes utilize historical user mobility patterns to determine the user’s trajectory while some are based on contextual knowledge or user activity patterns.

Mobility pattern based mobility prediction techniques assume that movements of a user follow a specific pattern. If the history of the user’s movement is not available for prediction, the prediction scheme becomes useless. For instance, such schemes are not very efficient if a user is situated in a new location for which no past history is available. Moreover, recent changes of the user’s behavior do not have considerable influence on the prediction scheme when mobility history is logged for a long time [57].

In contextual knowledge based techniques, mobility is predicted using environmental knowledge and user contextual information such as real world maps, user profile and user's preferences. A large amount of information is required to make accurate predictions and it is difficult to keep this information up to date [63].

User activity based approaches predict user mobility using the locations of interest, preference and their probable entry and exit times [63]. Such schemes require careful selection of parameters to produce realistic results. Moreover, they may require a high level of computation and a large set of input data.

Many attempts were made to address the issue of user mobility prediction by both channel reservation and user mobility prediction schemes [3]-[8], [12]-[15], [24], [27], [28], [34], [36], [41]-[47], [54], [55], [57]-[58], [60]-[64], [67]-[69], [72], [73], [75], [77]. The discussion of some of the techniques related to user mobility prediction follows.

First, we discuss schemes which employ user mobility in channel assignment. These schemes can be considered as a step towards user mobility prediction schemes.

In [100], the *moving direction* (MD) method for Dynamic Channel Assignment (DCA) is proposed. In this method, information regarding the direction of movement of the MS is used for assigning channels that can possibly result in a reduction of the CDP. In this way, sets are formed of MSs moving in similar directions and they are assigned the same channel. In this arrangement, when a mobile of one set crosses a cell boundary, probably another member of the same set did the same crossing from its cell to the next cell, increasing the chances of its continuing usage of the same channel at handoff. This method reduces channel changes and call drops. Furthermore, the MD method promises

better performance when used in single dimension cell configuration systems with many expressways and fast moving vehicular traffic[78].

Speed and Moving Direction (SMD) method for DCA was proposed in [101]. It focuses on scenarios where both fast moving and slow moving MSs are part of the same system. Slow moving mobiles rarely require handoff and usually use the same cell and channel. Fast moving mobiles are typically in a greater need of handoffs. When such fast moving mobiles are assigned the same channel as a slow moving mobile, there are higher chances of call drops. To overcome this problem, channels are assigned based on mobile speeds. Specifically, only fast moving mobiles are assigned channels using the MD method. This choice increases the performance of the system, except in certain situations where the MSs change speeds or change the state of motion during a call. In these situations, the system performance suffers [78].

Some other user mobility prediction schemes are summarized below.

In [64] Tabbane proposed that a MS's location can be obtained from its quasi-deterministic mobility behavior and it can be represented as a set of movements in a user profile. This method was further pursued by Liu and Maguire in [43], who proposed a Mobile Motion Prediction (MMP) scheme for prediction of the future location of a roaming user according to his/her movement history patterns. The MMP scheme consists of a regularity-pattern detection component (RPD), which is used to detect specific patterns of user movement from a properly structured database, and a Motion Prediction Algorithm (MPA), which is invoked for combining the regularity information with stochastic information. Thus, one can reach a decision/prediction on the future location(s) of the MS. Simulation results presented in [43] show that the prediction efficiency of the proposed MPA algorithm is about 95%. The main drawback of

algorithms proposed in [64] and [43] is their high sensitivity to changes in the user's pattern of movement.

In [41] a Gauss-Markov process is used to model the user's mobility pattern. The Gauss-Markov model captures the correlation of the mobile's velocity in time, and it can represent different user mobility patterns, including the random walk and constant velocity fluid-flow models. Based on the information gathered from the user's last report of location and velocity, the network predicts the future location of MS.

In [5], the next cell is predicted using the histories of handovers and the classifications of locations. The information of handovers is stored in a profile server, which translates historical data into mobility profiles. Mobility patterns of MSs are represented by these profiles.

In [6], Bhattacharya and Das proposed an adaptive algorithm for location management. It can learn mobility patterns of MSs by keeping a dictionary of each MS's path updates. However, this algorithm is very sensitive to random user movements and it is not scalable for a large number of users.

In [42], a hierarchical location-prediction (HLP) algorithm is proposed. It uses a pattern matching algorithm and an extended self-learning Kalman filter for next-cell prediction based on cell sequence observations, signal strength measurements, and cell geometry assumptions. HLP consists of global prediction and local prediction components. Global prediction is used to predict the inter-cell movement trajectory of a user by matching the user's actual path to one of the existing mobility patterns, while local prediction is used to predict the intra-cell movements of the mobile users. User mobility patterns are stored in a database and fed to an approximate pattern matching algorithm to allow estimation of a MS's inter-cell movement direction. A Kalman

estimator deals with the randomness in user movement by tracking intra-cell trajectory. Analysis and simulation results presented in [42] have shown that a self-adaptive extended Kalman filter provides high degree of accuracy for next-cell location and instantaneous speed prediction. However, the acceleration of a MS is represented by a Gaussian stochastic process, which makes the model unrealistic [102].

A data mining approach was presented in [75] for prediction of user movements. In this approach, user mobility patterns are mined from the history of mobile user trajectories and the MS's next movement is predicted by using mobility rules, which are extracted from the user mobility patterns. In [68] and [72], data mining methods such as clustering and association rule mining are used for exploring mobility patterns.

[79], [80], [81] and [82] propose different ways to estimate handoff parameters from information on the flow of vehicles along a road network. In [79], Nakano et al. proposed the basic idea of an approximate technique to analyze the blocking probability in the 2-dimensional cellular systems using spatial data. Ref. [81] analyzes the forced termination probability based on the technique proposed in [79]. It is assumed that calls are generated by MSs on vehicles moving along a road network. Ref. [81] suggests that in order to provide fair service to users, the structure of the road network and the traffic flow on the road network should be considered during the design of the cellular networks.

An adaptive fuzzy inference system is developed in [59] to predict the probabilities that a mobile user will be active in the nearby cells at future moments using the real-time measurement data of the pilot signal powers received at the mobile user from the BSs. The prediction is obtained using the Recursive Least Square (RLS) algorithm.

Schemes proposed in [34], [83], [84] and [85] use neural networks in their mobility predictions.

In [34], a multilayer neural network (MNN) model is designed for mobile movement prediction. The MNN, which is based on the back-propagation learning algorithm, is trained with respect to the data obtained from the movement pattern of a MS for making predictions. The role of the neural network is to capture the unknown relationship between the past and the future values of the movement pattern. The performance of the method has been verified for prediction accuracy by considering different movement patterns of a MS and learning accuracy of the MNN model.

In [86], a method based on information theory is proposed. Each MS collects a set of “clues” such as its position in a particular road and its stay time during its previous displacements. These clues are then processed by the current cell to predict the future cell. The use of information theory and decision trees allows the choice of the most relevant clues for prediction. The disadvantage of this method is the need to store these clues in the MS itself, which consumes memory, and then energy and bandwidth when communicating this information to the BS [87].

In [87], a mobility prediction method based on modeling a MS’s behavior by a colony of ants is proposed. This method examines the previous displacements of the MS, and those of its neighbors, and then predicts its future location. The mobility model of [88] is used. This method is based on the work carried out by planning organizations and uses statistics drawn from five years surveys on users’ displacements. It simulates a set of users’ displacements during a number of days. Generated displacements are based on each user’s activity (work, study, etc.), the localization of the places of these activities (house, work places, schools) as well as the ways which lead to these places. The

simulation results show that one displacement can be predicted with a very high degree of accuracy even if the mobile history lacks some information.

Unlike many other schemes predicting user trajectory, schemes proposed in [57] and [63] are not based on the use of historical movement patterns. The scheme proposed in [57] predicts the traveling trajectory and the destination of the user utilizing the available contextual knowledge and spatial conceptual maps. The contextual knowledge is applied to a mathematical reasoning engine to predict the MS's future locations. Such a scheme might be more efficient in situations where past history of users is not available.

In [63], a mobility prediction scheme based on activity prediction was proposed, where user's mobility traces are used to determine the locations of interest, preference and their probable entry and exit times. Based on this, the MS's future locations and paths are predicted.

Section 3.4 presents a classification of PMOCR schemes.

3.4 Classification of predictive mobile-oriented channel reservation schemes

A classification of PMOCR schemes which already include the user mobility prediction component follows below [119].

Some schemes try to predict the next cell to which MS may handoff (single-cell prediction schemes) [12], [13], [15], [24], [36], [45], [46], [55], [62], [73], while others try to determine a set of cells MS may visit during its lifetime (multi-cell prediction schemes) [3], [27], [76].

Some schemes predict the location of handoff, i.e. to which cell MS may handoff next [12], [13], [45], [46], while other schemes not only predict the location but also predict the time of handoff [3], [15], [24], [27], [36], [55], [62], [73],[76].

Based on the information employed in the prediction process, PMOCR schemes can be categorized into three types. The first type of schemes base their prediction on current mobility parameters of mobile users [24], [12], [36], [46], [73]. The second type of schemes base the prediction on observation histories of users and/or cells [76], [15], [45], [55]. The third type of schemes combine information about current mobility parameters and observation histories in their predictions [3], [13], [27], [60], [62]. A detailed discussion and a survey of these schemes follow below. Refer to Table 3.3 for the summary of the classification of PMOCR schemes.

Table 3.3: Classification of predictive mobile-oriented channel reservation schemes.

Classes			Comments	References
Predicted cell count	Single-cell (next-cell)		Predict the next cell to which MS may handoff.	[12], [13], [15], [24], [36], [45], [46], [55], [62], [73]
	Multi-cell		Predict a set of cells MS may visit during its lifetime.	[3], [27], [76]
Temporal/Spatial HO prediction	Location of HO		Predict where MS may handoff.	[12], [13], [45], [46]
	Time and location of HO		Predict when and where MS may handoff.	[3], [15], [24], [27], [36], [55], [62], [73], [76]
Parameters used in prediction	Observation histories	Mobile-specific histories	Prediction is based on history of MS's mobility.	[3], [13], [76]
		Cell-specific histories	Prediction is based on history of cell's mobility.	[15], [27], [62]
		Mobile-specific histories and cell-specific histories	Prediction is based on history of MS's and cell's mobility.	[45], [55]
	Current mobility parameters	RSSI based parameter sampling	Mobility parameters are sampled using RSSI.	[24]
		GPS based parameter sampling	Mobility parameters are sampled using GPS or any other positioning technology.	[3], [12], [13], [27], [36], [46], [62], [73]

3.4.1 Prediction based on current mobility parameters

Schemes using current mobility parameters (velocity, direction, angle or distance) in their prediction typically compute a probability of events occurring, depending on the values of these parameters. The parameters can be sampled using either radio measurements such as the Received Signal Strength Indication (RSSI) or by positioning technologies like GPS [54]. GPS is the most widely employed positioning technology for determining the current mobility parameters. Schemes using GPS or other positioning technologies assume that positioning hardware is embedded in each MS, and the MS periodically transmits this mobility information to the current BS.

The key limitation of such approaches is the requirement that MSs must be equipped with positioning hardware. However, GPS is already widely available, and it is likely that it will be integrated in most of the communication devices in the near future.

In [12], a Predictive Channel Reservation (PCR) scheme is proposed. This scheme makes reservations for each MS based on its current position and orientation. The position measurement can be made using GPS or any other positioning technique and orientation details can be gathered from two consecutive position measurements taken during a small time interval. Using the position/orientation information, the BS extrapolates the future path of the MS. The next cell to which MS will handover is predicted based on the projected path. This scheme uses the *threshold distance* concept when reserving channels from neighboring cells. The threshold distance is defined as the radius of a circle which is co-centered with a cell, and this circle is smaller than the cell's coverage area. The area between these two circles is called the channel reservation area.

When a MS enters the reservation area of a cell from the inner part of that cell (or a new call is generated inside the reservation area), and if at the same time, it is heading to a new cell, a reservation request will be sent to that new cell's BS. If the MS changes its direction or terminates before reaching the new cell boundary, the reservation is deemed invalid (false reservation) and a cancellation of reservation request is sent to de-allocate the reserved channel. Rather than strictly mapping each reserved channel to the mobile that made the reservation, the set of reserved (PCR) channels at any moment is used as a generic pool to serve handoff requests, but not new calls. Once a handoff is needed, the BS will randomly choose a reserved channel from the reservation pool and will assign it to the handoff call.

In this scheme, the prediction method utilizes only the position and the orientation of a MS, it does not consider the velocity. Hence, one unvarying threshold distance is defined for all MSs, which may have different motion patterns. If it is very slowly moving, a MS located in the reservation area may take too long to cross the boundary of the cell. Since this type of an MS is almost stationary, the channel reserved in the adjacent cell may not be used for the session of the call. This can result in low bandwidth utilization.

The ACR (Adaptive Channel Reservation) scheme is proposed in [73]. It introduces the *threshold time* concept in order to address the problems of the Predictive Channel Reservation scheme proposed in [12]. Like [12], ACR is also based on GPS measurements. It is assumed that each MS has a different threshold distance but it has the same threshold time since all MSs have diverse relative moving speeds. The time it takes for a MS to reach the border of its target cell is predicted using the current moving

speed, orientation and location information. A channel reservation request is sent to the target cell when predicted handoff time of MS is less or equal to the threshold time.

The common shortcoming of both PCR [12] and ACR [73] schemes is the communication overhead which is an outcome of the message passing involved in sending reservations and cancellation of false reservations. Moreover, both of the schemes consider only a single type of traffic which makes them unsuitable for multimedia applications.

The scheme proposed in [24] eliminates the Hierarchical Location Prediction (HLP) for global inter-cell direction of [42] and utilizes only the local movement prediction and real-time position measurements to predict the next cell of MS. Like the scheme proposed in [42], this scheme also uses an extended Kalman filter to improve the accuracy of prediction. The extended Kalman filter plays a crucial role in computing the arriving probabilities to neighboring cells and predicting the next cell, where handoff calls should be accepted. However, extended Kalman filter is not optimal and may lead to divergence due to the nonlinear nature of the system [103].

In [24], Hu and Sharma considered multiple classes of traffic (interactive video, videophone, telephony/voice, www browsing and e-mail) instead of only single-class calls, and they modified the PCR of [12] to improve handoff priority. They also analyzed the time for handoff-request submission from the MSs to the destination BS. They provided a way to determine a time instance (reservation deadline) by which the bandwidth assignment for the arriving handoff call should be completed, and suggested that handoff-request reservations should take place before the actual acceptance of handoff calls. Hence, a MS submits a handoff reservation request to the new BS when

the RSS in the current BS is below the threshold level, and the RSS in the next-cell's BS is high enough to allow receiving signals from the MS.

In the approach proposed by [36], each MS's current position and speed are used to estimate when and where the MS will cross a cell boundary and enter another cell. It is assumed that the BSs have road-map information and the MSs have GPS. The BSs estimate the speed and moving direction of the MSs, based on the location information of the MSs at two consecutive periods. The BSs estimate the probability that the MSs will enter the neighboring cells based on their velocity and the road-map information. The BSs then compute the amount of bandwidth to be reserved, based on such estimation. Ref. [104] argues that the influence of the MS movement randomness on the prediction accuracy is not considered sufficiently in [36]. Moreover, the approach proposed in [36] is based on an unrealistic assumption that the BSs have the road-map information.

3.4.2 Prediction based on observation histories

Schemes based on observation histories use historical movement patterns of users in order to calculate their possible future locations. It is assumed that movements of a MS follow a specific pattern and show some regularity. Some schemes use mobile-specific histories in their predictions, some use cell-specific histories, while others employ both mobile and cell-specific histories to predict the path of a MS.

The key limitation with all history-based schemes is the overhead to develop, store and update traffic histories for the different cells. These histories may not always be reliable as they constantly go through changes [12].

In [45], Lu and Bharghavan investigated next-cell mobility prediction for an indoor wireless system based on both user-specific and cell-specific profiles. It is assumed that

each cell and MS has a profile, and a set of cells form a universe, which is divided into distinct geographical regions called zones. Each zone has a profile server, which maintains user-specific and cell-specific profiles and using these profiles calculates the next-predicted cell. Cell profiles are used when MS profiles are not available. This scheme, defines a MS to be static if it remained in the same cell for a certain threshold period of time; otherwise the MS is defined as mobile. Bandwidth is reserved only for a mobile MS in the next-predicted cell, and QoS for its connections are kept at the pre-negotiated minimum level. A default algorithm is used for prediction in the absence of any profile information. One of the drawbacks of the proposed scheme is that it does not provide the estimation for the channel holding time.

In [15], the mobility of the MS is predicted using handoff histories of mobile users observed over time in the cell. For each MS which moves into an adjacent cell from the current cell, the BS caches a quadruplet for MS, is the quadruplet includes the time when the mobile departed from the current cell, the index of the previous cell the mobile had resided in before entering the current cell, the index of the cell the mobile entered after departing from the current cell, and the sojourn time of the mobile in the current cell (the time span between the entry into and departure from the current cell).

From the cached quadruplets, the BS builds a handoff estimation function, which describes the estimated distribution of the next cell and sojourn time of a mobile, depending on the cell the mobile stayed before. The handoff probability is calculated using the handoff estimation function. It is used to determine the amount of bandwidth to be reserved. On the other hand, analysis for computing the CDP and CBP is not provided.

The mobility prediction scheme proposed by Yu and Leung in [76] is motivated by the computational learning theory, which has shown that prediction is synonymous with data compression. From the observation that a connection originated from a cell follows a specific sequence of cells, rather than a random sequence of cells, the scheme utilizes a character compression technique to predict the future mobility of MSs.

The proposed mobility prediction scheme is similar to the character-based version of the Ziv-Lempel algorithm. This method records the mobility profile of each user by a sequence of events. The sequence of events (new call, handoff or end of call) during the lifetime of a call corresponds to a substring in the Ziv-Lempel algorithm. For each event, the call's elapsed time and cell ID number is recorded. The next term of the mobility profile sequence is predicted from its previous events. The output of the algorithm is the handoff probability from cell i to cell j . The probabilistic predictions of next possible events are derived using the outputs of the algorithm. Based on the predictions, a most likely cell-time (MLCT) of the MS, and a cluster of cells when and where a MS is most likely to visit in the future is constructed.

When a call is admitted, bandwidth is reserved in the MS's MLCT. This scheme assumes that channel holding time follows a general distribution. Therefore, it is more realistic than the schemes assuming exponential distribution [37], which do not give an accurate representation of the real characteristics of cellular networks. The main advantage of the proposed scheme is that it is applicable to arbitrary cell topologies, so it is not restricted to a commonly used structured cell configuration such as hexagonal. However, this scheme is not suitable for future mobile communications as it considers only voice calls and does not consider soft handoff, in which a MS can communicate with two BSs simultaneously.

3.4.3 Prediction based on current mobility parameters and observation histories

Schemes discussed in this section employ both current mobility parameters and observation histories in their predictions.

In [60], Soh and Kim proposed a scheme that adapts the amount of reserved bandwidth in a cell according to real-time handoff predictions made by individual MSs with integrated GPS receivers. Contrary to the majority of the schemes in which hexagonal or circular boundaries are assumed, this scheme considers irregular cell boundaries. It approximates the boundary of the cell as a series of points around the BS, computed using previously recorded handoff locations. It uses linear extrapolation from a MS's recent positions to predict its handoff cell and time. Recently, Soh and Kim enhanced this scheme to employ road topology knowledge in addition to the MS's positioning information [62]. As in [36], this approach assumes that the BSs have road-map information and the MSs have a positioning system. The positioning information is used only for predicting the MS's future handoff time and target cell, in order to adjust the reservations. It is not used to decide whether a handoff should be initiated. The enhanced scheme of Soh and Kim uses both incoming and outgoing handoff predictions to achieve more efficient reservations, unlike most of the schemes that consider only incoming handoffs. This scheme consists of a mobility prediction module, which defines the prediction tasks to be performed by the individual BSs, and a dynamic bandwidth reservation module, defining the way both incoming and outgoing handoff predictions are used to adjust the reservation at each BS. The mobility prediction module requires that active MSs periodically report their position to the serving BS, which performs the predictions using the obtained data.

The information required for making predictions, including the road topology within the radio coverage area of the BS, is stored in a database which is maintained by the BS. The database has to be updated regularly. After each update, the BS starts collecting the data required for the next update. The prediction algorithm identifies a set of possible paths that may result in a handoff within a specific period of time. The bandwidth reservation module reserves some bandwidth for incoming handoff calls. The amount of reserved bandwidth is updated regularly, based on mobility predictions.

One of the main advantages of the scheme proposed by Soh and Kim is that it considers irregular shapes for cells, which makes it more realistic than other schemes proposed. The major difference between this scheme and the scheme proposed in [67] is that Soh and Kim's scheme uses the previous history of handoffs for the mobile users passed through a BS to estimate the time of handoff for the current user in that BS. The main weakness of this scheme is the unrealistic assumption that each BS stores the road topology within its radio coverage area.

A first-order auto-regressive filtering technique is used in [3] in order to determine a set of cells that are most likely to be visited (Most Likely Cluster) by a MS on its route. This approach reserves resources in all possible future cells that the MS may visit for the time interval during which the MS will reside in each cell. The direction of MS is predicted using the history of MS's movement. At any time instance, the directional-probability of any cell being visited next by a MS can be derived based on angle ratios related to the current cell where the mobile resides, and the estimated direction of the MS at that time instance.

The fundamental property of this probability distribution is that for a given direction, the cell that lies in the estimated direction from the current cell has the highest

probability of being visited in the future. The current direction of the MS may be determined using radio measurements or GPS. The claim is that, this method guarantees that the predicted mobile direction is not affected by small deviations in the MS's direction, and that it converges rapidly to the new direction of the MS. The downside of this scheme is that directional-probabilities are calculated using only directionality measures, without taking into consideration other important factors such as the call duration.

Choi and Kim [13] proposed a scheme in which next cell is predicted based on the MS's mobility graph, which stores user's mobility patterns in a compact form. The mobility patterns of MSs are collected by a Mobility Pattern Profile (MPP). This profile includes the index of a cell in which the user is currently residing, the index of the previous cell in which the user resided before entering the current cell, the index of a cell that the user has entered previously after leaving the current cell, and the number of times the user has moved from the current cell to another cell. Each node in the mobility graph represents a visited cell and edges represent the directions of the mobile user. The amount of bandwidth to be reserved is determined by a Threshold of Mobility Probability (TMP); more bandwidth will be reserved for users with a mobility probability above the TMP than for those below the TMP.

The mobility probability of the MS to move from cell i to cell j through cell p is calculated using the mobility profile stored in the graph. The traffic is classified into real-time and non-real-time. Bandwidth is reserved only for real-time calls due to the nature of their delay-sensitivity. However if a MS with real-time call resides in a particular cell for a long period of time before handoff, network bandwidth may be wasted due to earlier bandwidth reservation. A two-tier cell structure was employed in

order to prevent such a problem. The Pilot Signal Strength (PSS) of the MS is used to determine the MS's location in the cell. MSs with PSS above the average signal strength are assumed to be in "Tier-1" as MSs with PSS below the average signal strength are assumed to be in "Tier-2". The BS reserves bandwidth of its neighboring cells to support handoffs of MS only in "Tier-2", since these cells have a higher probability of moving to another cell than those in "Tier-1". The main drawback of this scheme is the overhead to develop, store and update traffic profiles for different cells.

In [27] Islam and Murshed proposed a scheme in which mobility prediction employs an enhanced Cell Visiting Probability (CVP) estimator to define a set of cells most likely to be visited by a MS (the shadow cluster, SC). The SC is comprised of the neighboring cells having higher probability for a MS to visit. The CVPs are calculated using mobility parameters (position, direction and speed) and Expected Travel Distance (ETD) of the cell from the position of MS. It is assumed that each MS is equipped with GPS and it periodically transmits mobility information to its current BS, which informs all the neighboring cells for which the CVPs of this MS is significant.

The mobility information obtained is used to calculate CVPs to form SCs and estimate Reservation Time Window (RTW). The RTW of a MS in each cell of the SC is estimated using ETD and its standard deviation. ETD between two cells is estimated using the aggregated history of observations made when a MS moves between them. Moreover, ETD and average speed are used to estimate the expected arrival time and departure time of the MS for each cell in the SC. Using these estimates, for each cell in SC, the feasibility of supporting the newly originated service during the MS's expected residence time, is verified, and accordingly, resources are reserved.

The bandwidth reservation in cells within the SC is updated whenever the MS hands off from one cell to another, and when the direction of a MS goes beyond the angular span of the SC. This update in reservation results in the formation of a new SC and a re-calculation of CVPs. This scheme classifies traffic as real-time and non real-time (rate-adaptive). To ensure the continuity of real-time (non-rate-adaptive) connections, bandwidth is borrowed from the existing adaptive services without affecting the minimum QoS guarantees. This scheme suffers from high complexity of operations performed and a communication overhead.

3.5 Predictive mobile-oriented channel reservation schemes and their characteristics

Table 3.4 contains the characteristics of the PMOCR schemes presented in section 3.4. We provide a discussion on some of these characteristics below.

Table 3.4: Characteristics of predictive mobile-oriented channel reservation schemes.

Scheme	Predicted cell count	Temporal/ Spatial HO prediction	Parameters used in prediction	Traffic type	Cell shapes
<i>Chiu and Bassiouni [12]</i>	single-cell	location of HO	GPS based parameter sampling	homogeneous	circle
<i>Xu et al. [73]</i>	single-cell	time and location of HO	GPS based parameter sampling	homogeneous	circle
<i>Hu and Sharma [24]</i>	single-cell	time and location of HO	RSSI based parameter sampling	multimedia	circle
<i>Lee and Hsueh [36]</i>	single-cell	time and location of HO	GPS based parameter sampling	homogeneous	hexagon
<i>Choi and Shin [15]</i>	single-cell	time and location of HO	cell-specific histories	homogeneous	hexagon
<i>Yu and Leung [76]</i>	multi-cell	time and location of HO	mobile-specific histories	homogeneous	variable
<i>Soh and Kim [62]</i>	single-cell	time and location of HO	GPS based parameter sampling and cell-specific histories	multimedia	variable
<i>Aljadhai and Znati [3]</i>	multi-cell	time and location of HO	GPS based parameter sampling and mobile-specific histories	multimedia	hexagon
<i>Choi and Kim [13]</i>	single-cell	location of HO	GPS based parameter sampling and mobile-specific histories	multimedia	hexagon
<i>Islam and Murshed [27]</i>	multi-cell	time and location of HO	GPS based parameter sampling and cell-specific histories	multimedia	hexagon

Predicted cell count: It is crucial for PMOCR schemes dealing with multi-cell predictions to provide very accurate predictions as unnecessary bandwidth reservations may lead to a low bandwidth utilization and high signaling overhead because of the message passing involved in sending reservations to other BSs.

Temporal / Spatial HO prediction: In order to efficiently utilize the bandwidth, it is essential for PMOCR schemes to provide not only the location but also the time of handoff.

Parameters used in prediction: All history-based schemes suffer from the overhead to develop, store and update traffic histories. The key limitation of the schemes employing positioning technology in their predictions is the requirement that MSs must be equipped with some kind of positioning hardware. Combining history and position information might provide better results. History-based measurements may supply an initial idea of the movements in the cell, while positioning may be employed to adjust the MS's movement predictions with time according to its actual movements [77].

Traffic type: It is important to note that PMOCR schemes dealing with homogeneous traffic only are not suitable for future wireless networks, as they are expected to provide support for a broad range of multimedia services.

Cell shapes: To simplify the analysis, the majority of PMOCR schemes assume that cell boundaries are hexagonal, circular or square. In reality, the cell boundary is fuzzy and is irregularly shaped due to terrain characteristics and obstacles that interfere with radio propagation [62]. Therefore, schemes assuming regular shapes are not suitable for real networks, as they may contain complex boundaries, cells of various size and shape, and multiple overlapping cells covering a single physical area [97].

Chapter 4

PRIORITIZED NEW CALL QUEUING POLICY

This chapter presents a detailed discussion of the PNCQ policy and it is organized as follows. Section 4.1 introduces the concept of *queuing threshold time*. Calculations of the time MS will remain in the current cell are offered in Section 4.2. Section 4.3 provides a flow diagram of the PNCQ policy.

4.1 Queuing threshold time

The PNCQ policy does not treat all new calls equally. It differentiates new calls based on the time the MS is predicted to spend in the current cell. The priority is given to calls with higher remaining time in the cell by providing them with an exclusive limited FIFO queue. Such a priority scheme is chosen due to the fact that when a new call is blocked, the mobile user will most likely reattempt to originate a new connection [111]. Therefore, mobile users with higher remaining time will likely originate more new calls than mobile users with lower remaining time. Thus, giving priority to calls with higher remaining time will reduce the CBP of new calls, resulting in an increase in total carried traffic.

The PNCQ approach introduces a *queuing threshold time* (t_q) parameter in order to differentiate among calls with high and low remaining times. t_q is a constant time value which may vary from cell to cell. The calls with remaining times above this threshold are queued providing that the queue has sufficient amount of slots.

4.2 Remaining time

It is assumed that mobility parameters (speed, orientation and location) of each MS are sampled using GPS or any other positioning technology. According to the current moving speed, orientation and location information of each MS, the BS can predict the time within which the MS will reach the boundary of its current cell (t_b). t_b can be calculated using the method provided in [22].

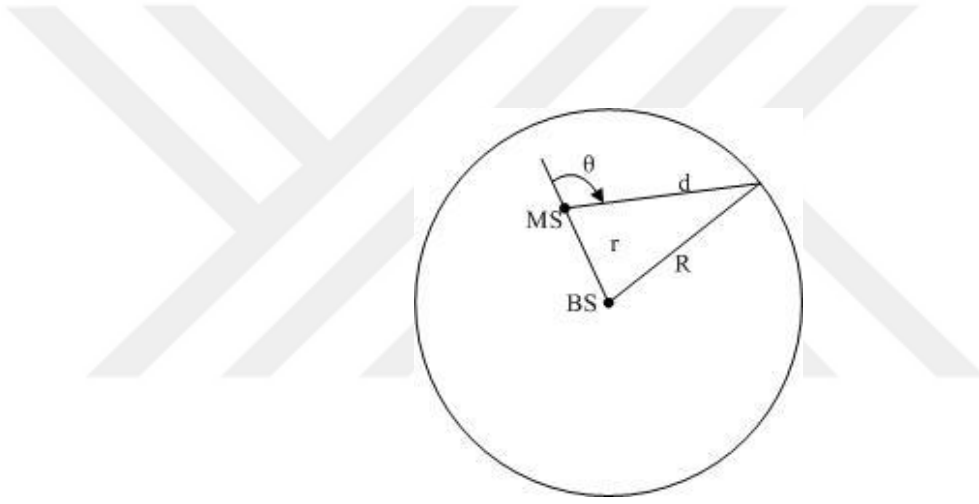


Figure 4.1: Illustration of distance from MS to the cell boundary.

The following formula calculates the distance (d) between the MS and the cell boundary (refer to Figure 4.1):

$$d = [R^2 - (r \sin \theta)^2]^{1/2} - r \cos \theta \quad (4.1)$$

where R is the radius of the cell, r is the distance from the BS to MS and θ is the direction of MS's travel. BS is assumed to be at the center of the cell.

The time MS will remain in the current cell (t_b) is predicted using the following formula:

$$t_b = d/v \quad (4.2)$$

where v is the speed of the MS. In formulas (4.1) and (4.2) v , r and θ mobility parameters are assumed to be sampled using GPS.

If $t_b \geq t_q$ and the queue is not full, then the MS is queued. t_b is periodically recalculated. The MS continues to be queued until $t_b < t_q$.

However, in case a user is stationary, $v = 0$, the call should be queued without calculating the remaining time.

4.3 Flow diagram of the Prioritized New Call Queuing policy

The PNCQ policy assumes that if a new call attempt has failed, the user will reattempt to start a new connection after some period of time or terminate. This assumption is based on the behavior of users in real-life cellular networks [111]-[114].

Figure 4.2 illustrates the flow diagram of the PNCQ approach.

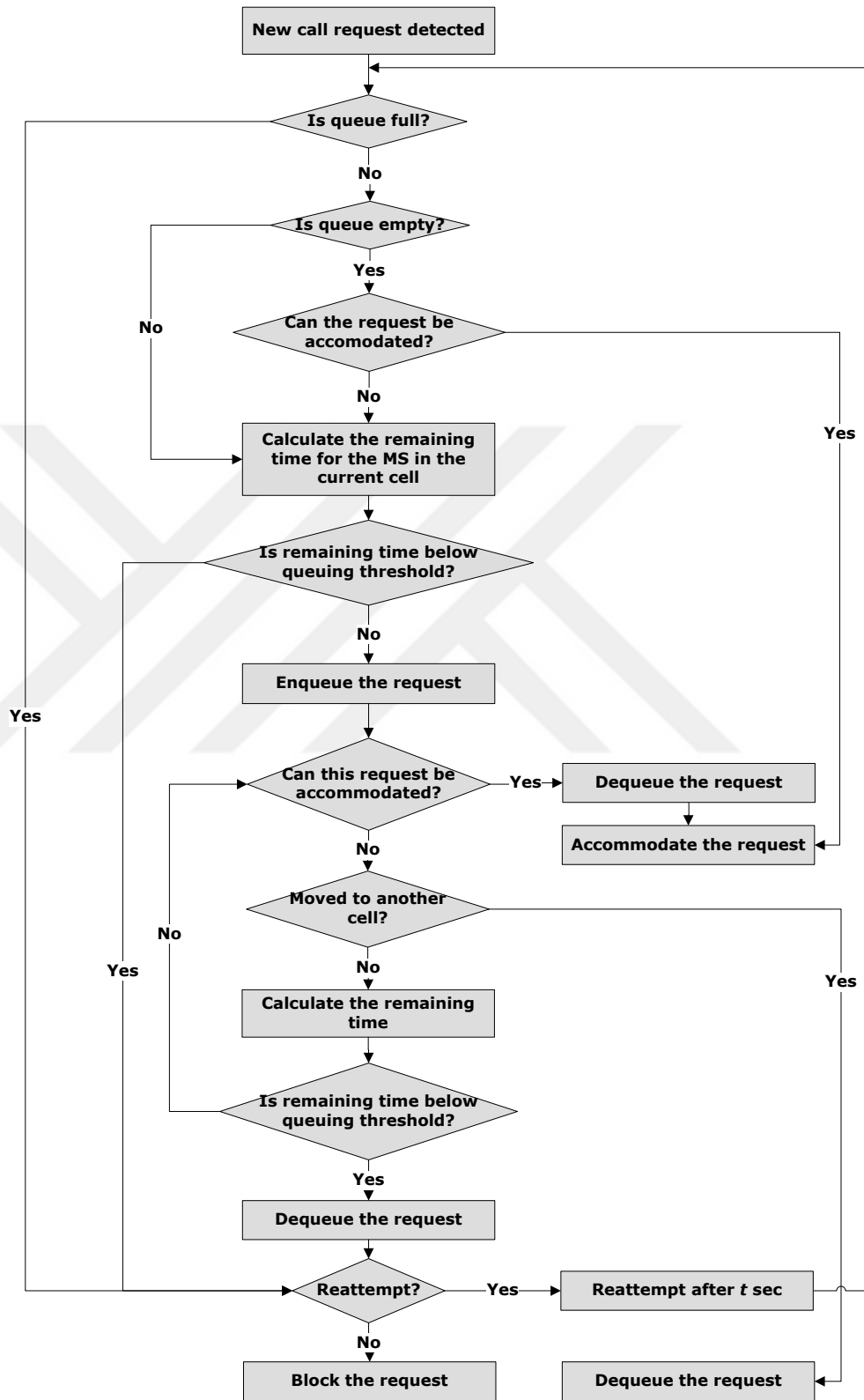


Figure 4.2: Flow diagram of the PNCQ policy for mobile users.

Chapter 5

TRAFFIC MODELS

This chapter describes the traffic models of PNCQ_GC and SNCQ_GC schemes and is organized as follows. Section 5.1 provides a discussion on the main characteristics of a general traffic model. Then, traffic models of PNCQ_GC and SNCQ_GC schemes are presented in Sections 5.2 and 5.3, respectively.

5.1 Characteristics of a traffic model

To develop the traffic models of our schemes, we first analyzed the behavior of a single reference cell in cellular networks. We assume that the traffic of the reference cell is classified into real-time and non real-time. Moreover, it is assumed that γ portion of blocked new calls will reattempt to obtain a connection, while $(1 - \gamma)$ will terminate due to user impatience.

The call arrival process, call service time and cell dwell time are three important characteristics of a traffic model [70]. When considering redials, reattempt time should also be taken into consideration [111]. These characteristics are discussed below in detail.

5.1.1 Call service time

We assume that the call service time of all the calls entering the cell is an exponentially distributed random variable with parameter μ_s . Hence, average call service time $E[T_s]$ is exponentially distributed with mean $1/\mu_s$ [113], [114], [70]:

$$E[T_s] = 1/\mu_s. \quad (5.1)$$

5.1.2 Cell dwell time

The mean dwelling time in a cell, i.e. the time spent by a MS before handing over to a neighboring cell, is assumed to follow a two-dimensional fluid flow model [70], in which the average outgoing rate of a MS within a cell is given by:

$$\mu_d = E[v]L/(\pi A) \quad (5.2)$$

where $E[v]$ is the mean of speed v of MSs, L is the length of the cell perimeter and A is the area of the cell. Therefore, the average cell dwell time $E[T_d]$ has a random exponential distribution with mean $1/\mu_d$:

$$E[T_d] = \pi A / (E[v]L). \quad (5.3)$$

5.1.3 New call reattempt time

The time between two successive reattempts for blocked new calls is an exponential random variable with rate μ_r . Thus, the average new call reattempt time $E[T_r]$ is exponentially distributed with mean $1/\mu_r$ [113], [114]:

$$E[T_r] = 1/\mu_r. \quad (5.4)$$

5.1.4 Call arrival process

The call arrival process in one cell is influenced by the gross arrival of all the calls and call reattempt requests originated by γ portion of blocked new calls. $(1 - \gamma)$ portion of the blocked new calls terminate without reattempting [111]. The flow of all the calls excluding reattempts is modeled as a Poisson process whose rate is λ . Handoff calls account for a portion of α in λ and new calls account for a portion of $(1 - \alpha)$ in λ . The gross arrival rate excluding redials (λ) is given by:

$$\lambda = \lambda_h + \lambda_n. \quad (5.5)$$

The arrival rate of handoff calls (λ_h) is given by:

$$\lambda_h = \alpha\lambda. \quad (5.6)$$

The arrival rate of new calls (λ_n) is given by:

$$\lambda_n = (1 - \alpha)\lambda. \quad (5.7)$$

Real-time calls account for a portion of δ in handoff and new calls. Hence, real-time handoff call arrival ($\lambda_{rt,h}$) rate is given by:

$$\lambda_{rt,h} = \delta\lambda_h. \quad (5.8)$$

Substituting equation (5.6) in (5.8) we get:

$$\lambda_{rt,h} = \delta\alpha\lambda. \quad (5.9)$$

Real-time new call arrival rate ($\lambda_{rt,n}$) is given by:

$$\lambda_{rt,n} = \delta\lambda_n. \quad (5.10)$$

Substituting equation (5.7) in (5.10) we get:

$$\lambda_{rt,n} = \delta(1 - \alpha)\lambda. \quad (5.11)$$

Gross arrival rate of real-time calls is given by:

$$\lambda_{rt} = \lambda_{rt,h} + \lambda_{rt,n}. \quad (5.12)$$

Substituting equations (5.9) and (5.11) in (5.12) we get:

$$\lambda_{rt} = \delta\alpha\lambda + \delta(1 - \alpha)\lambda = \delta\lambda(\alpha + 1 - \alpha) = \delta\lambda. \quad (5.13)$$

Non real-time calls account for a portion of $(1 - \delta)$ in handoff and new calls.

Hence, non real-time handoff call arrival rate ($\lambda_{nrt,h}$) is given by:

$$\lambda_{nrt,h} = (1 - \delta)\lambda_h. \quad (5.14)$$

Substituting equation (5.6) in (5.14) we get:

$$\lambda_{nrt,h} = (1 - \delta)\alpha\lambda. \quad (5.15)$$

Non real-time new call arrival rate ($\lambda_{nrt,n}$) is given by:

$$\lambda_{nrt,n} = (1 - \delta)\lambda_n. \quad (5.16)$$

Substituting equation (5.7) in (5.16) we get:

$$\lambda_{nrt,n} = (1 - \delta)(1 - \alpha)\lambda. \quad (5.17)$$

Gross arrival rate of non real-time calls is given by:

$$\lambda_{nrt} = \lambda_{nrt,h} + \lambda_{nrt,n}. \quad (5.18)$$

Substituting equations (5.15) and (5.17) in (5.18) we get:

$$\lambda_{nrt} = (1 - \delta)\alpha\lambda + (1 - \delta)(1 - \alpha)\lambda = (1 - \delta)\lambda(\alpha + 1 - \alpha) = (1 - \delta)\lambda. \quad (5.19)$$

The gross arrival rate including connection reattempts (λ') is given by:

$$\lambda' = \lambda + \lambda_r. \quad (5.20)$$

where λ_r is the arrival rate due to repeated new calls. λ_r is calculated using the following equation [113], [114]:

$$\lambda_r = \gamma E[N_b] \mu_r. \quad (5.21)$$

where γ is a portion of blocked new calls that try to reestablish a connection and $E[N_b]$ is the expected number of blocked new calls.

5.2 Traffic model of the Prioritized New Call Queuing policy combined with Guard Channels (PNCQ_GC)

Figure 5.1 depicts the traffic model of the PNCQ_GC scheme. It is assumed that $(c - k)$ channels are reserved exclusively for real-time and non real-time handoff calls. All calls arrive into the cell with the arrival rate λ . With probability α , an arrived call is treated as a handoff call, and with probability $(1 - \alpha)$ as a new call. A handoff call is served if there is a sufficient number of channels available, otherwise it is dropped. Furthermore, with probability β , new calls are treated as calls with $t_b < t_q (NC_{nq})$, which are not allowed to be queued, while with probability $(1 - \beta)$ new calls are treated as calls

5.3 Traffic model of Simple New Call Queuing policy combined with Guard Channels (SNCQ_GC)

The traffic model of the SNCQ_GC scheme is portrayed in Figure 5.2. PNCQ_GC and SNCQ_GC schemes have similar traffic models. The only difference is that the SNCQ_GC scheme allows queuing of all new calls, while the PNCQ_GC scheme only queues the new calls with $t_b \geq t_q$.

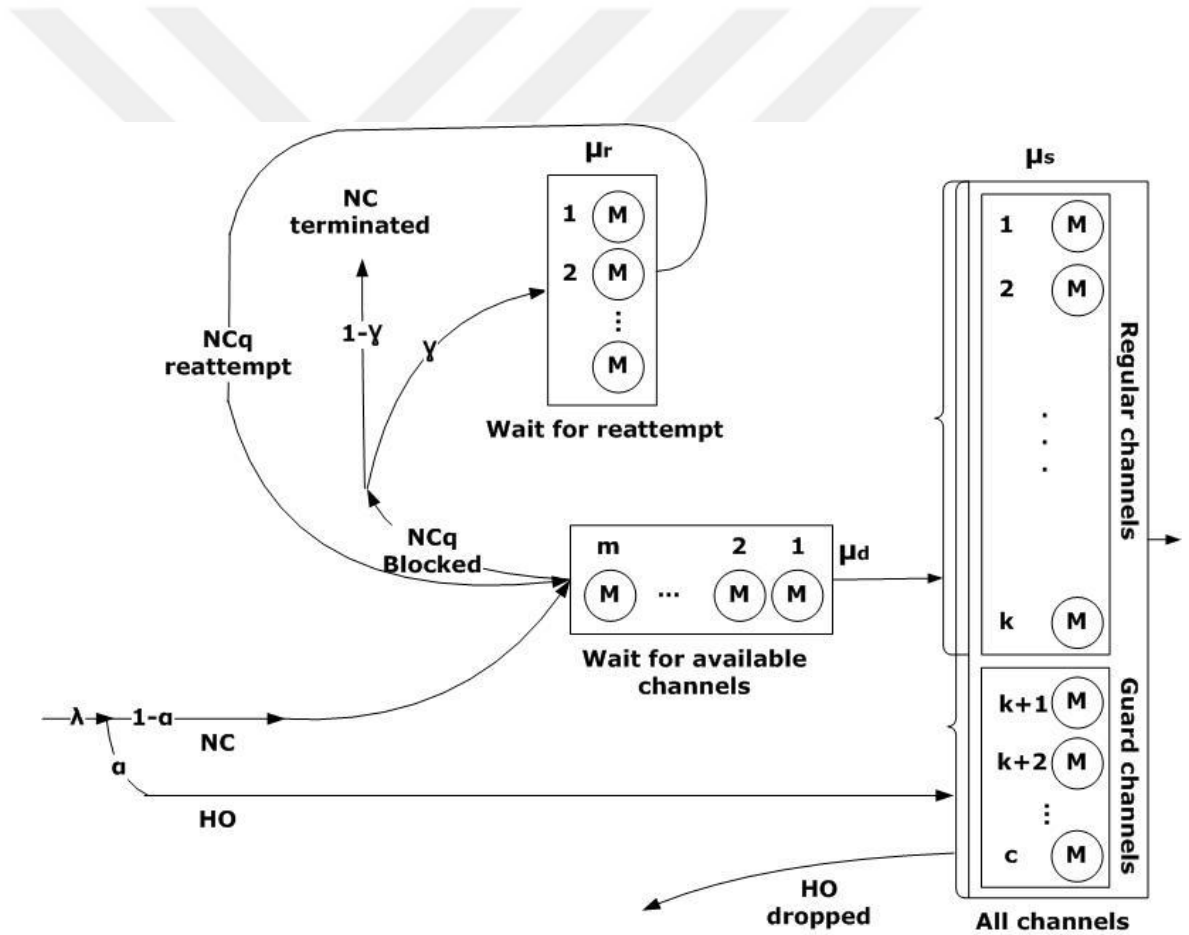


Figure 5.2: Traffic model of the SNCQ_GC scheme.

Chapter 6

SIMULATION MODELS

This chapter presents the simulation tool, models, parameters and outputs used in this thesis. The organization of this chapter is as follows. Section 6.1 discusses the simulation tool used in this study. The simulation models are provided in Section 6.2. Section 6.3 covers the definitions of the simulation parameters. Finally, Section 6.4 gives an overview of the performance measures.

6.1 Simulation tool

A computer simulation is a computation that models some real or imagined system over time. Computer simulation makes it possible to analyze systems that would be expensive, dangerous or even impossible to construct. The goal of simulation is to evaluate performance characteristics of the system. The behavior of a system as it evolves over time is studied by developing a simulation model. This model usually considers a set of assumptions concerning the operation of the system. Simulation can be used in the design of a new system to check the design variants before implementation. It can also be used in the analysis of an existing system to investigate different modes of operation outside the real system [116].

In this study, all simulation studies were developed using the GPSS World simulation tool. GPSS World is based on the seminal language of computer simulation, GPSS, which stands for General Purpose Simulation System [117]. This language was developed primarily by Geoffrey Gordon at IBM around 1960, and has contributed important concepts to every commercial discrete event Computer Simulation Language developed ever since. GPSS World is a direct descendent of GPSS/PC, an early implementation of GPSS for personal computers. It facilitates the statistical analysis required of any serious simulation project. In summary, it is a self contained environment with everything from built-in probability distributions to automatic experiment generation, for screening as well as for optimization [117].

6.2 Simulation models

Simulation model of the Fully Shared Scheme (FSS) was developed before simulation models of other schemes. Hence, FSS model is our base model. Other simulation models were actually derived from FSS.

6.2.1 Fully Shared Scheme (FSS)

In FSS, handoff and new calls are treated equally. All available channels are shared by handoff and new calls. Flowchart of the FSS simulation model is given in Figure 6.1.

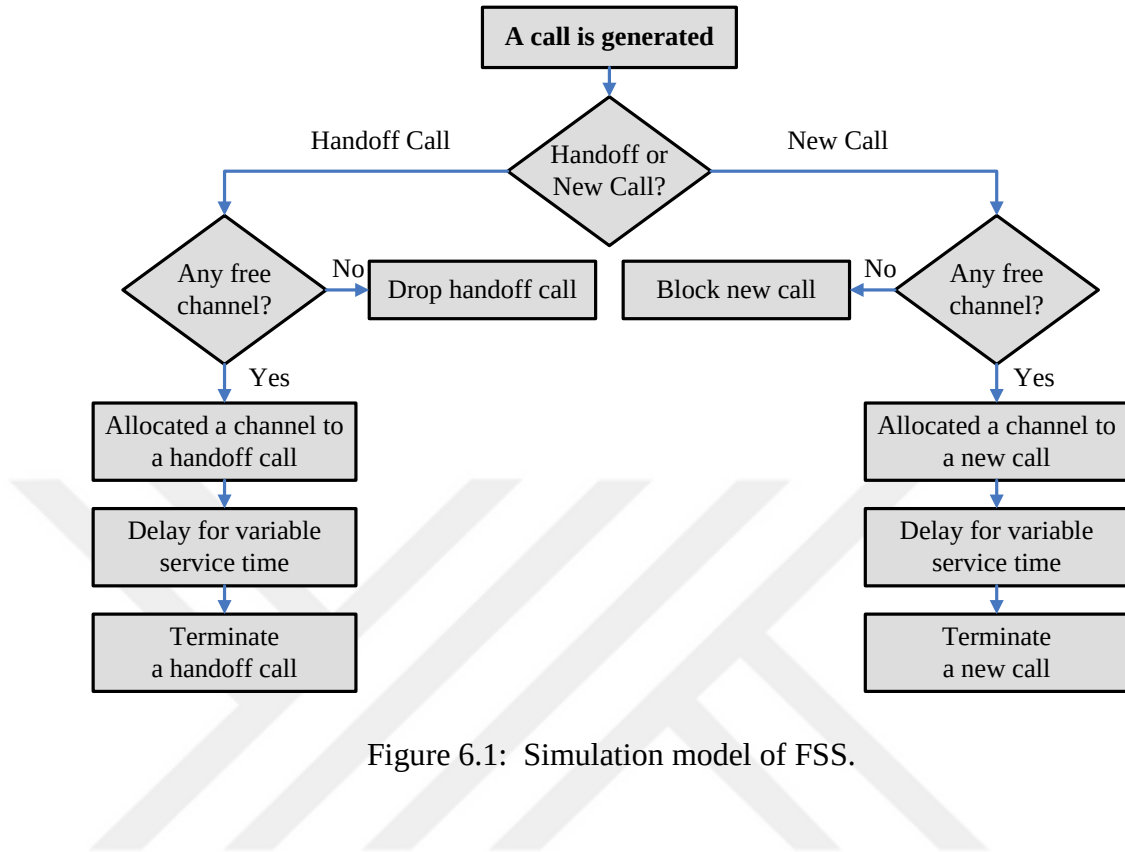


Figure 6.1: Simulation model of FSS.

6.2.2 Guard Channel scheme with single class of traffic

The simulation model of GC scheme with single class of traffic was derived from the model of FSS presented in Section 6.2.1. In this scheme, priority is given to handoff attempts by assigning C_h channels exclusively for handoff calls among the C channels in a cell. The remaining $C - C_h$ channels are shared by both new and handoff calls. A new call is blocked if the number of available channels in the cell is less than or equal to C_h when the call is originated. A handoff attempt is unsuccessful if no channel is available in the target cell. Figure 6.2 shows the flowchart of the simulation model, where C represents total number of channels, C_a - number of already allocated channels and C_h - number of channels reserved for handoff calls.

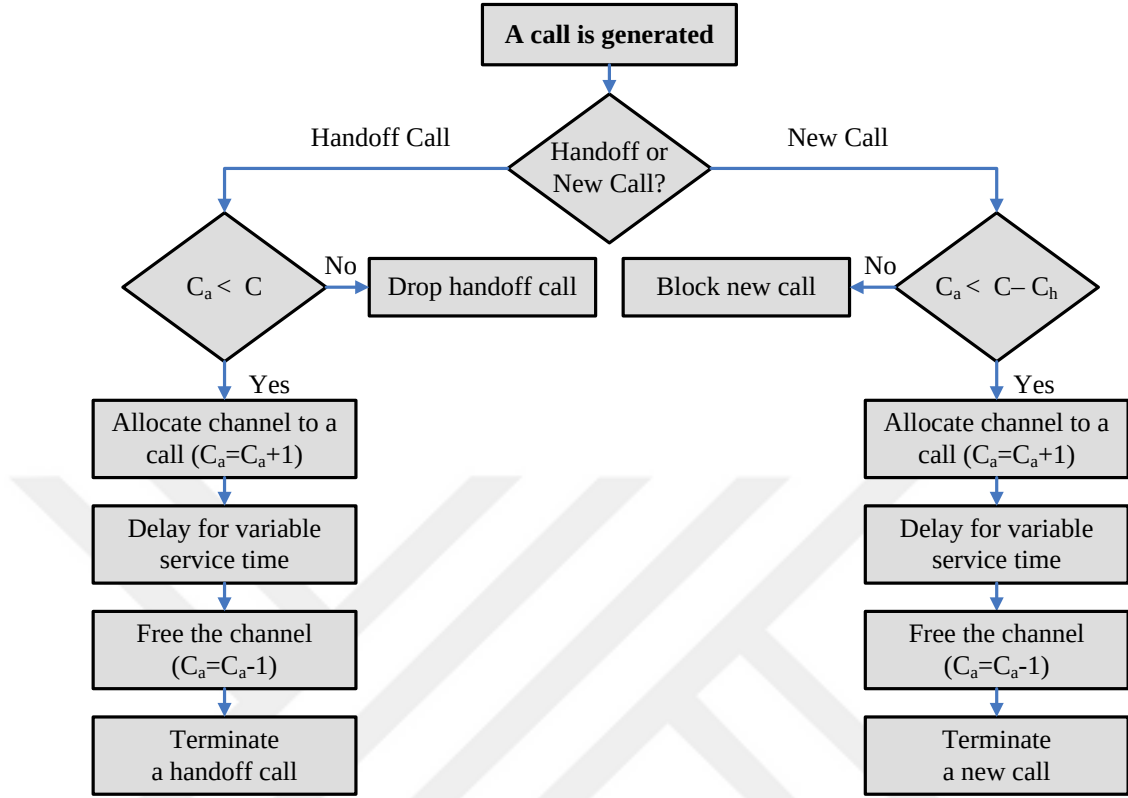


Figure 6.2: Simulation model of GC scheme with single class of traffic.

6.2.3 Guard Channel scheme with multiple classes of traffic

The simulation model of GC scheme with multiple classes of traffic was obtained from the model of GC scheme with single class of traffic presented in Section 6.2.2. In this scheme, distinction is made between handoff and new calls and no distinction is made between real-time and non real-time calls. Among the C channels in a cell, C_h channels are exclusively reserved for real-time and non real-time handoff calls. The remaining $C - C_h$ channels are shared by both real-time and non real-time new and handoff calls. A new call is blocked if the number of available channels in the cell is less than or equal to C_h , when the call is originated. A handoff attempt is unsuccessful if no

channel is available in the target cell. Flowchart of the simulation model is given in Figure 6.3. In the flowchart, C_r represents number of channels required for each call.

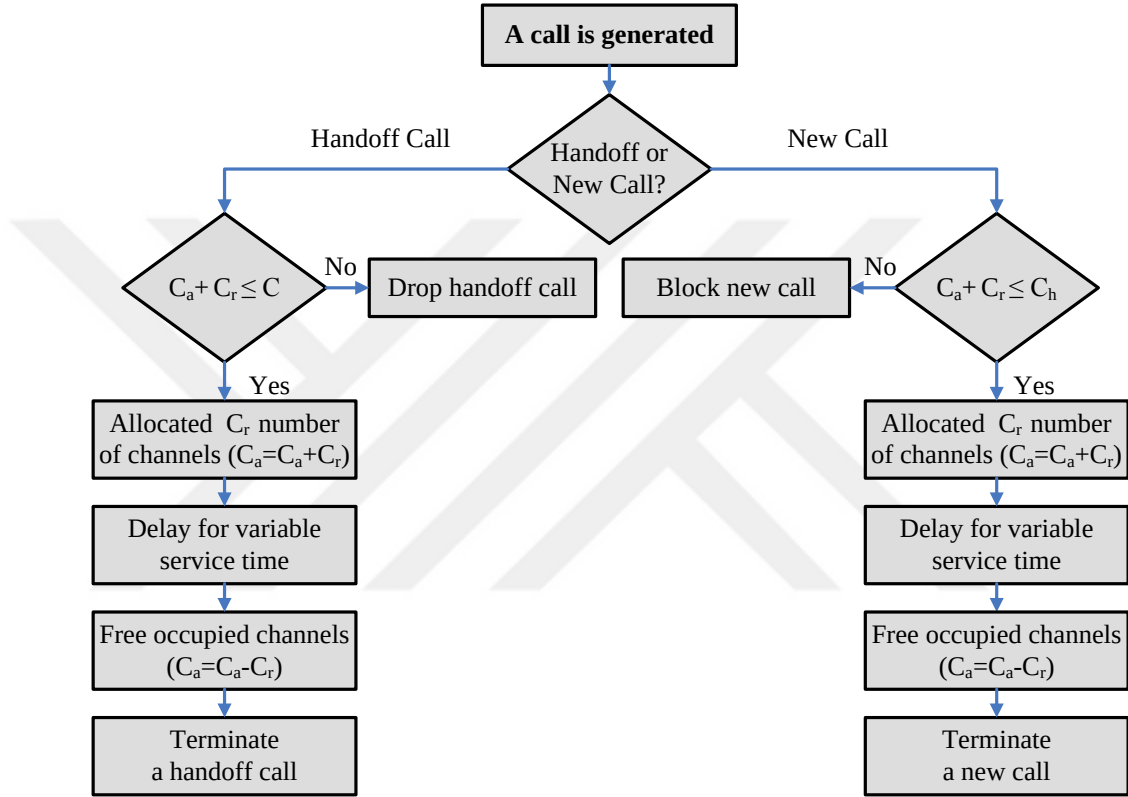


Figure 6.3: Simulation model of GC scheme with multiple classes of traffic.

6.2.4 Guard Channel scheme with multiple classes of traffic and new call reattempts

The simulation model presented in Section 6.2.3 was used as a base for this model. The two schemes are similar except that the model discussed in this section allows new call reattempts. It is assumed that when a new call cannot establish a connection, it will be either terminated or, a new connection request, which is treated the same as a new call, will be made after $1/\mu_r$ seconds. Each new call is allowed n retries [112]. Figure 6.4 illustrates the flowchart of the simulation model, where N_{ret} represents the total number of retries (reattempts) of a new call.

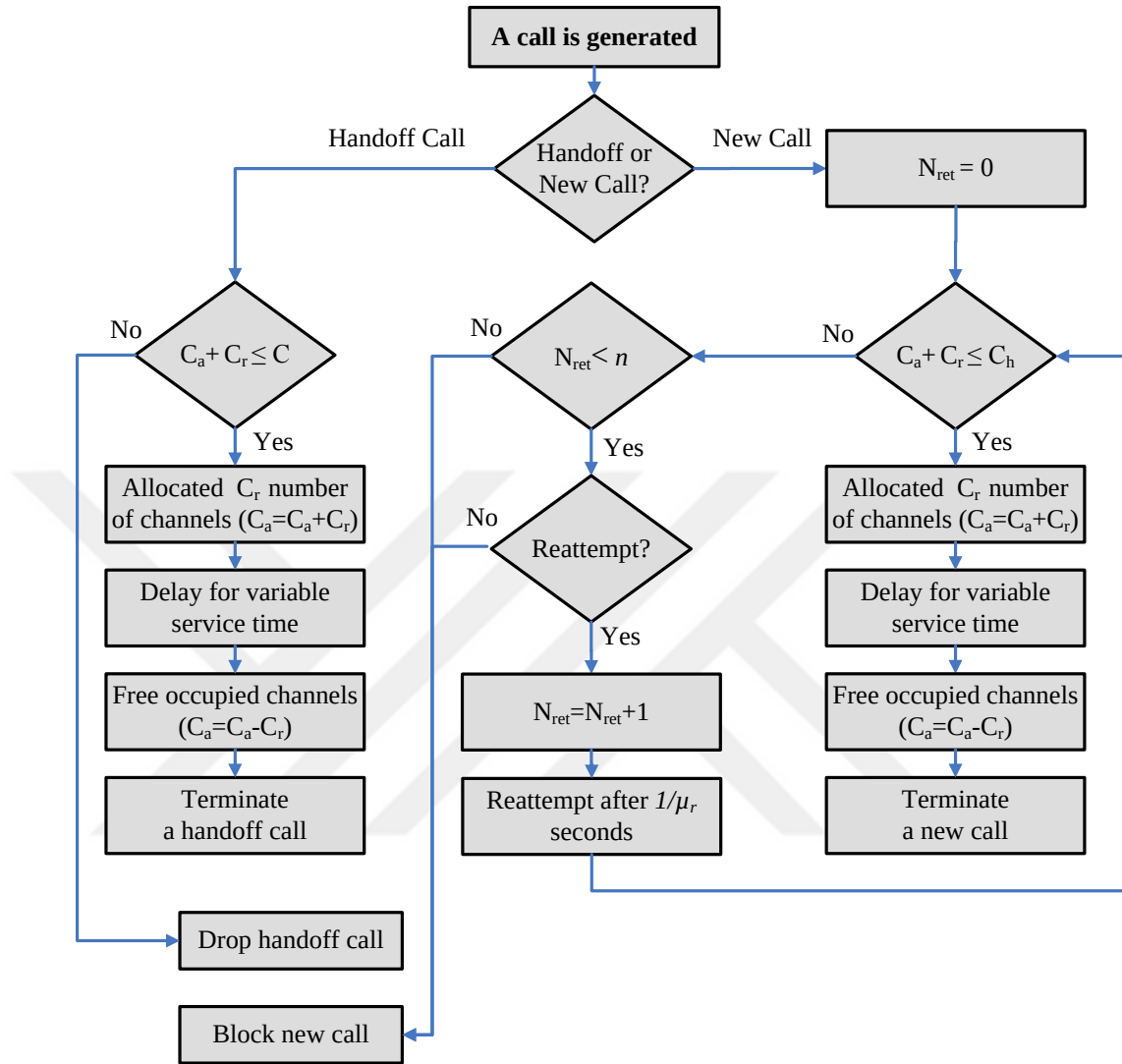


Figure 6.4: Simulation model of GC scheme with multiple classes of traffic and new call reattempts.

6.2.5 Simple New Call Queuing policy combined with Guard Channels (SNCQ_GC) and new call reattempts

This simulation model was attained from the model of the GC scheme with multiple classes of traffic and new call reattempts presented in Section 6.2.4. This scheme is analogous to the scheme discussed in Section 6.2.4, except that queuing of new calls is allowed if necessary. If there is no available channel for the new call, new call is queued. When a channel is released in a cell, it is assigned to the next new call waiting in the queue (if any). If more than one new call is in the queue, the FIFO queuing discipline is used. Flowchart of the simulation model is depicted in Figure 6.5.

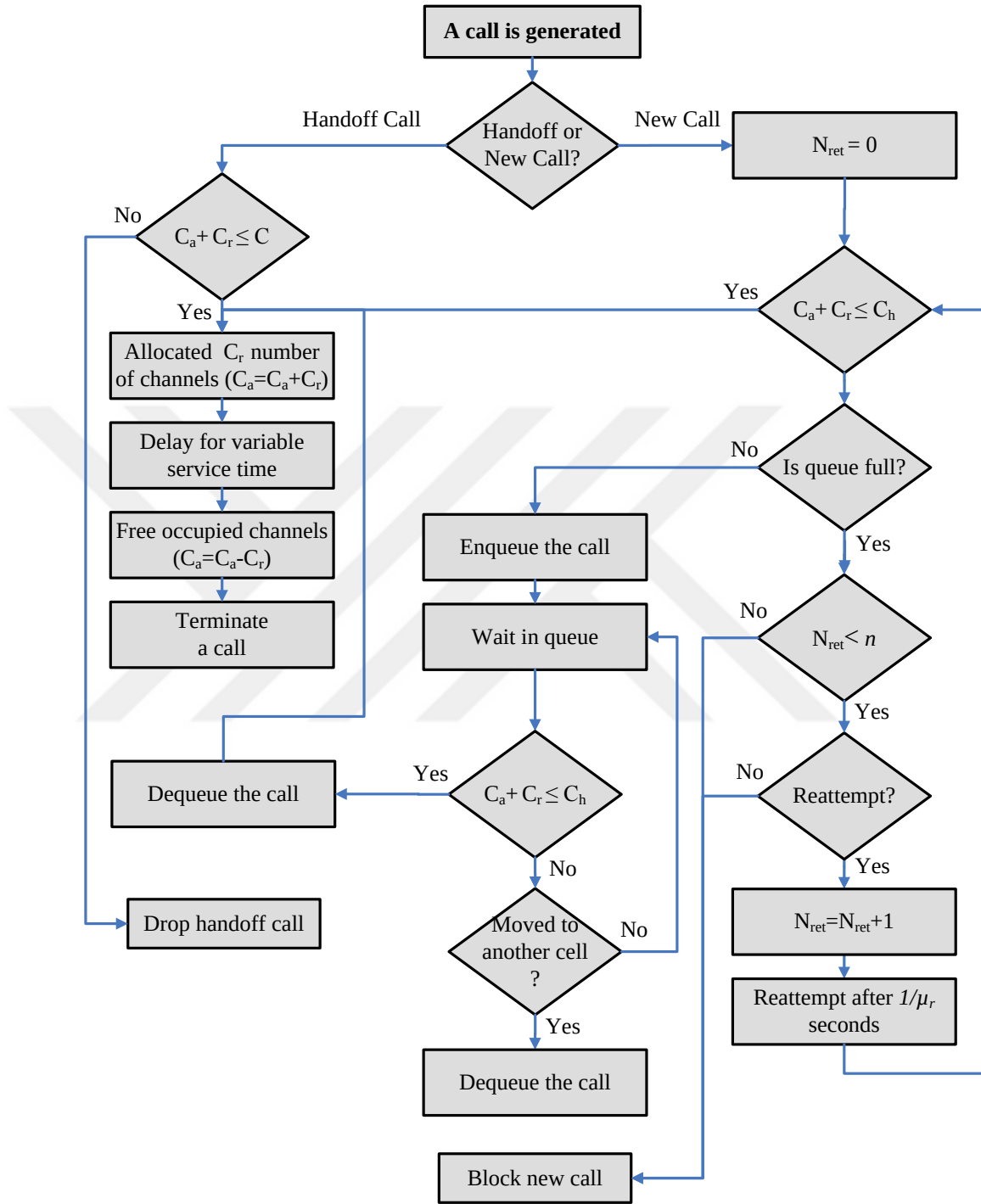


Figure 6.5: Simulation model of SNCQ_GC scheme.

6.2.6 Prioritized New Call Queuing policy combined with Guard Channels (PNCQ_GC) and new call reattempts

The simulation model of PNCQ_GC is based on the model of the SNCQ_GC scheme presented in Section 6.2.5. The two schemes are alike, apart from the queuing policy. In PNCQ_GC model, the time within which the MS will reach the boundary of its current cell t_b is calculated for a new call to be queued. Only new calls with remaining time t_b greater than queuing threshold time t_q are queued. The queued new call stays in the queue while t_b is greater than t_q . However, stationary mobile users are not considered in this simulation. If considered they should be queued without calculating the remaining time. Figure 6.6 illustrates the flowchart of the simulation model.

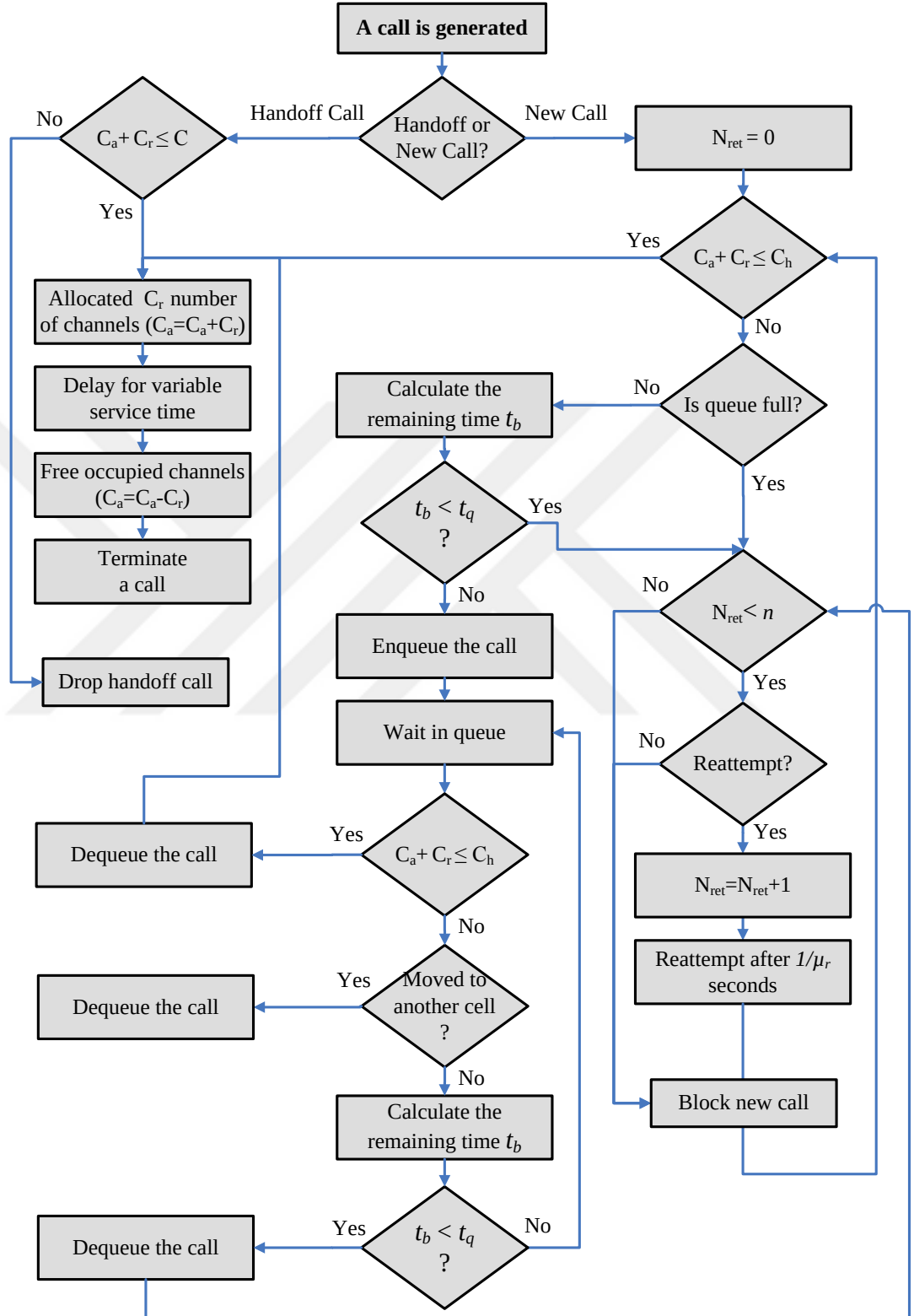


Figure 6.6: Simulation model of PNCQ_GC scheme.

6.3 Simulation parameters

Table 6.1 summarizes the definitions of simulation parameters used in this study.

Table 6.1: Simulation parameters.

Parameter	Definition
c	Total number of channels
h	Number of reserved channels
$1/\lambda$	Call interarrival time
$1/\mu_s$	Mean service time
$1/\mu_r$	Average new call reattempt time
$1/\mu_d$	Average cell dwell time
n	Maximum number of retries
t_q	Queuing threshold time
m	Queue length
α	Weight of handoff calls
β	Portion of new calls with $t_b < t_q$
γ	Portion of blocked new calls that try to reestablish a connection
δ	Weight of real-time calls

6.4 Performance measures

In this study, PNCQ_GC and SNCQ_GC schemes are evaluated based on Call Blocking Probability (CBP), Call Dropping Probability (CDP), Call Reattempt Probability (CRP) and utilization (U).

CBP is defined as follows:

$$CBP = N_b/N_{ncr} \quad (6.1)$$

where N_b is the total number of blocked (rejected) new calls and N_{ncr} is the total number of new calls including connection reattempts.

CDP is defined as follows:

$$CDP = N_d / N_{ho} \quad (6.2)$$

where N_d is the total number of dropped (rejected) handoff calls and N_{ho} is the total number of handoff calls.

CRP is defined as follows:

$$CRP = N_r / N_{ncr} \quad (6.3)$$

where N_r is the total number of new call retries.

Utilization is a degree to which a model makes an effective use of bandwidth. Its value is given as an output of the GPSS simulation tool.

Chapter 7

SIMULATION RESULTS

In this chapter, simulation results of the PNCQ_GC and SNCQ_GC schemes are investigated. These schemes are evaluated based on CRP, CBP, CDP and system utilization parameters. The chapter is organized as follows. The values of the simulation parameters are provided in Section 7.1. Section 7.2 presents the performance analysis of the PNCQ_GC scheme, while the performance comparison of PNCQ_GC and SNCQ_GC schemes is discussed in Section 7.3.

7.1 Values of the simulation parameters

In each simulation 1,000,000 calls were generated and each simulation was run 20 times to ensure that the obtained results are in the 95% confidence interval level (See Appendix A). Table 7.1 contains the values of the simulation parameters, which are based on the values employed in the related studies [111]-[114], [70].

In this study, we simulated the behavior of one circular cell with a radius R of 400 meters. One cell contains c channels, h of which are reserved for handoff calls [22]. The average call service time is exponentially distributed with mean $1/\mu_s$ of 120 seconds [113], [114], [70]. The call arrival process in one cell is influenced by the gross arrival of all the calls and call reattempt requests originated by γ portion of blocked new calls [111]-[114]. $(1 - \gamma)$ portion of the blocked new calls terminate without reattempting [111]. The flow of all the calls excluding reattempts is modeled as a Poisson process

whose rate is λ [22], [112]. The simulation results were obtained for various call interarrival time $1/\lambda$ values.

Moreover, handoff calls account for a portion of α in λ and new calls account for a portion of $(1 - \alpha)$ in λ [22]. δ portion of traffic in the cell is generated by real-time calls, which consist of voice and video calls. Non real-time calls constitute $1-\delta$ portion of the traffic and consist of data calls. Voice, data and video calls require the use of 1, 2 and 4 channels, respectively [27], [60], [62].

Furthermore, the average new call reattempt time is exponentially distributed with mean $1/\mu_r$ of 10 seconds and each new call is allowed 20 retries [112]. However, [120] and [121] suggest that these values are not realistic. They propose a simple model to estimate the expected number of retrials and redials per new call attempts, which is used to determine the effective load and the number of channels required to meet the grade of service.

Finally, based on the cell size and user speed, the cell dwell time of slow MSs, which can be calculated using Equation 5.3, ranges from 300 to 360 seconds. Hence, queuing threshold t_q is chosen to be 300 seconds in order to accommodate the MSs with high remaining time t_b .

Table 7.1: Values of the simulation parameters.

Parameter	Values
Total number of channels (c)	25
Number of reserved channels (h)	1, 4, 8
Call interarrival time ($1/\lambda$)	12, 10, 8, 6 sec.
Mean service time ($1/\mu_s$)	120 sec.
Average new call reattempt time ($1/\mu_r$)	10 sec.
Average cell dwell time ($1/\mu_d$)	300 sec.
Maximum number of retries (n)	20
Queuing threshold time (t_q)	300 sec.
Queue length (m)	1, 6, 11
Weight of handoff calls (α)	0.3
Portion of new calls with $t_b < t_q$ (β)	0.4, 0.5, 0.7
Portion of blocked new calls that try to reestablish a connection (γ)	0.5, 1.0
Weight of real-time calls (δ)	0.75, 0.8

7.2 Performance analysis of the PNCQ_GC scheme

In this section, we present the performance analysis of the PNCQ_GC scheme. We examine the impact new call reattempts, queue length, number of reserved handoff channels, queuing threshold and varying traffic conditions have on the system performance.

7.2.1 Impact of new call reattempts

Initially, we investigate the impact new call reattempts have on the system. The performance of PNCQ_GC with $\gamma = 0.0$, a scheme with no new call reattempts, and PNCQ_GC with $\gamma = 1.0$, a scheme in which all new calls will reattempt to establish a connection after being blocked, with $n = 20$, $h = 4$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$ and $\delta = 0.8$ are examined in this section.

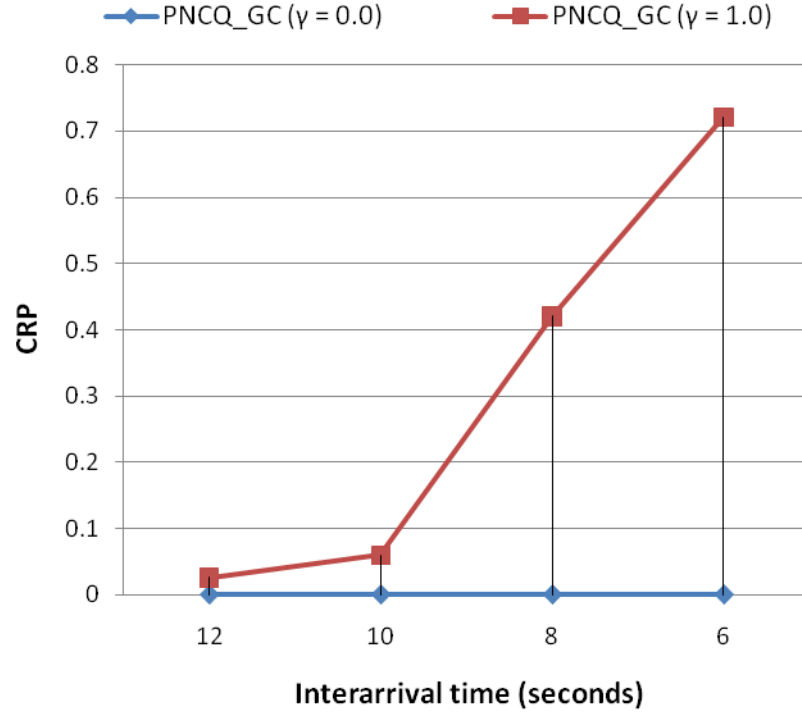


Figure 7.1: CRP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20$, $h = 4$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$ and $\delta = 0.8$.

Figure 7.1 shows that CRP for PNCQ_GC with $\gamma = 0.0$ is 0 for all the values of the interarrival time as there are no new call reattempts allowed in this model. On the other hand, PNCQ_GC with $\gamma = 1.0$ has high CRP as all new calls will reattempt until they establish a connection or reach a maximum number of reattempts n , which is set to 20.

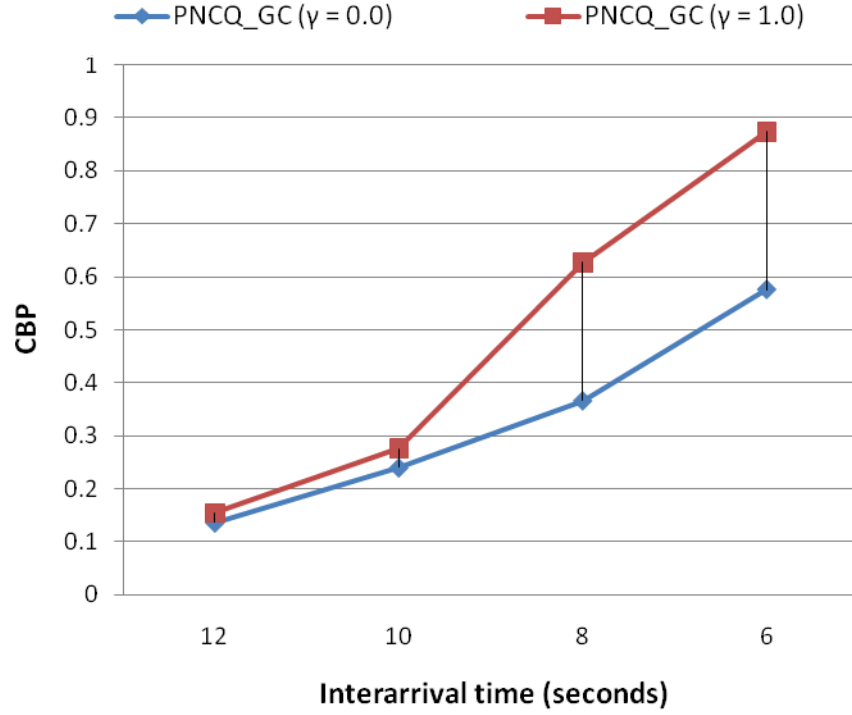


Figure 7.2: CBP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20$, $h = 4$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$ and $\delta = 0.8$.

Figure 7.2 indicates that, CBP for PNCQ_GC with $\gamma = 0.0$ is significantly lower than PNCQ_GC with $\gamma = 1.0$. This is due to the traffic load generated by new call reattempts, which in turn increases the CBP.

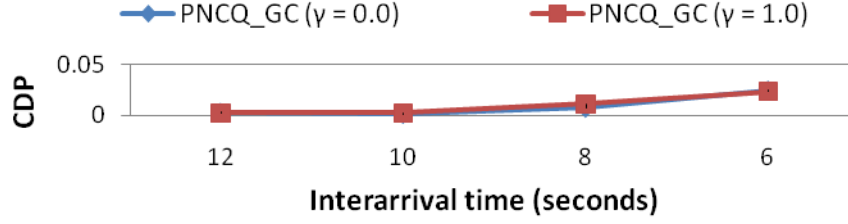


Figure 7.3: CDP versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20$, $h = 4$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$ and $\delta = 0.8$.

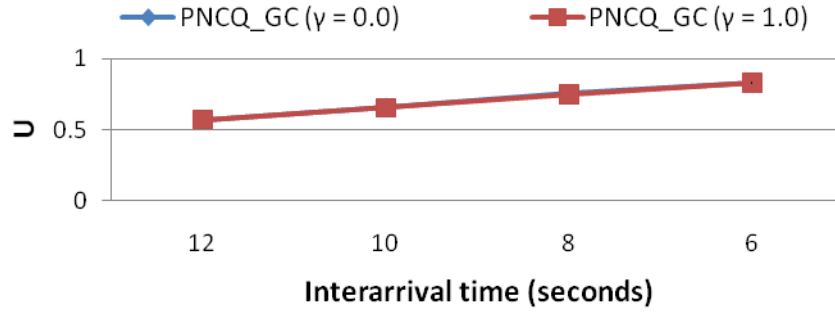


Figure 7.4: Utilization versus interarrival time for PNCQ_GC scheme for various γ values with $n = 20$, $h = 4$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$ and $\delta = 0.8$.

Examining Figures 7.3 and 7.4, it can be seen that, the CDP and utilization are not affected by the changing the γ value, as no changes are made from channel allocation point of view.

To sum up, we cannot neglect the repeated attempts as they have a negative impact on the system performance in terms of CRP and CBP.

7.2.2 Impact of the number of reserved handoff channels

We continue by exploring the effect of variation in the number of the reserved handoff channels on the system performance. PNCQ_GC schemes with 1, 4 and 8

reserved handoff channels are considered. The rest of the parameters are set as follows:
 $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$.

Figures 7.5 and 7.6 show that CRP and CBP values are increasing as the number of reserved channels increases. This is because more new calls are being blocked, which in turn results in a higher number of connection reattempts. PNCQ_GC with $h = 1$ has the lowest CRP and CBP values as it reserves the lowest number of channels for handoffs, leaving more channels for new calls. Moreover, it can be seen that CRP and CBP values are correlated. Values of CBP increase with CRP values, as more reattempts means more blocked new calls.

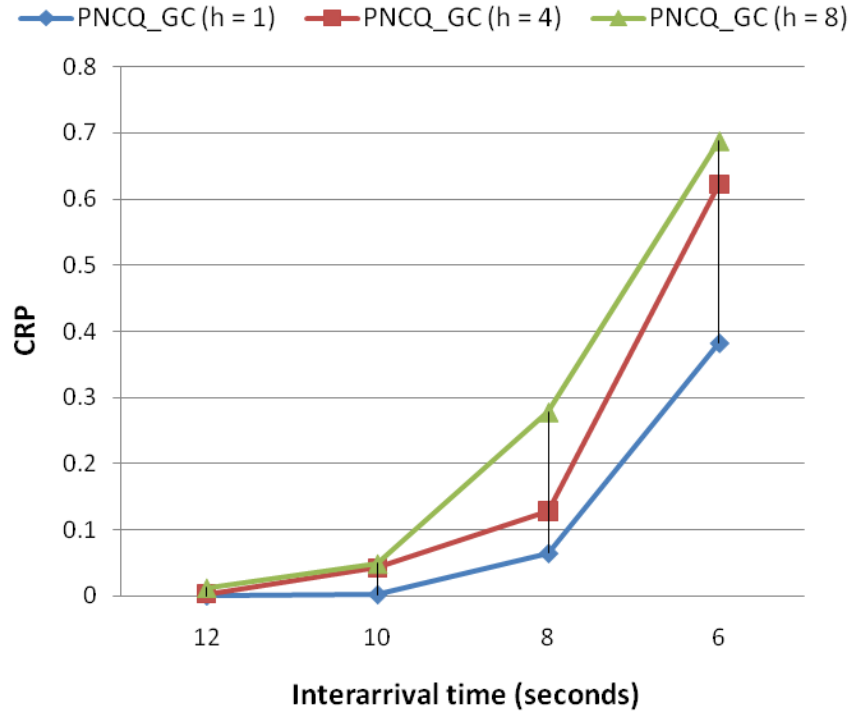


Figure 7.5: CRP versus interarrival time for PNCQ_GC scheme for various h values

with $n = 20, m = 6, \alpha = 0.3, \beta = 0.5, \gamma = 1.0$ and $\delta = 0.8$.

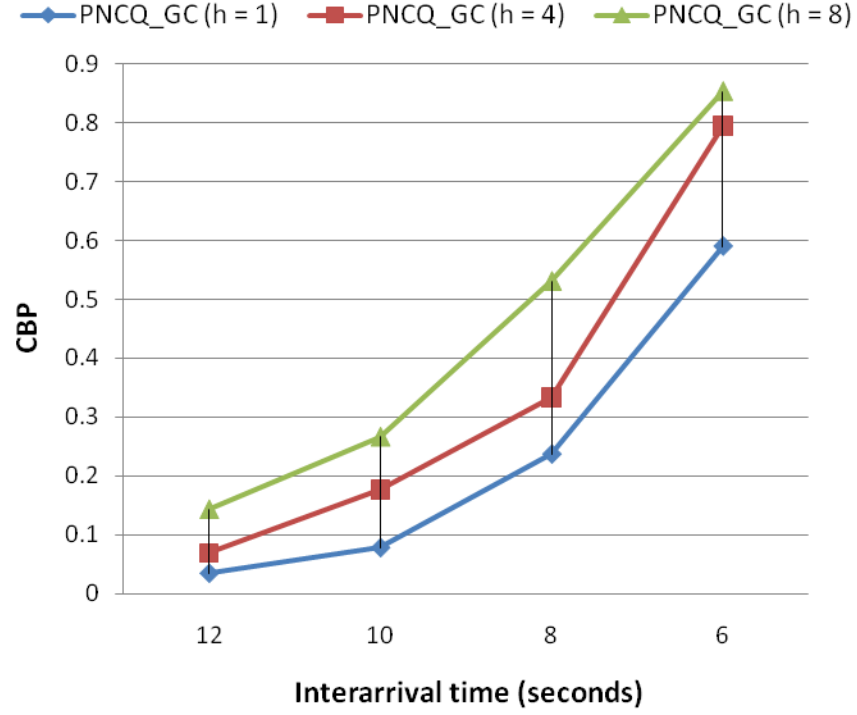


Figure 7.6: CBP versus interarrival time for PNCQ_GC scheme for various h values with $n = 20$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

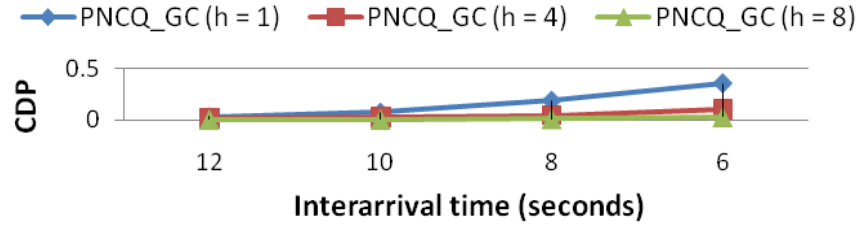


Figure 7.7: CDP versus interarrival time for PNCQ_GC scheme for various h values with $n = 20$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

By inspecting Figure 7.7 we can see that CDP is getting lower as the number of the reserved channels increases. This is due to the increase in the number of accommodated

handoff calls. PNCQ_GC with $h = 1$ has the highest CDP as it reserves the lowest number of channels.

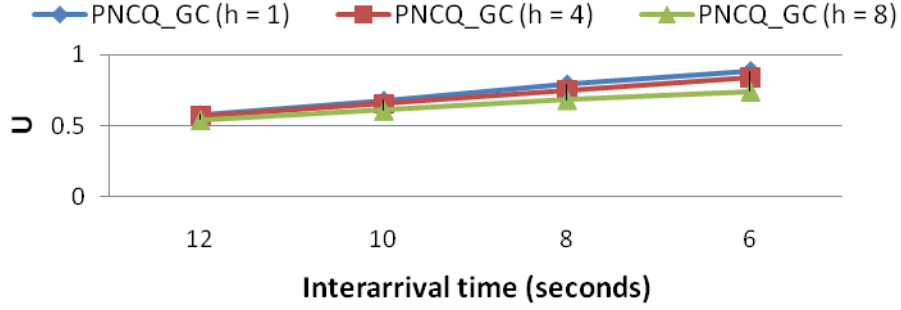


Figure 7.8: Utilization versus interarrival time for PNCQ_GC scheme for various h values with $n = 20$, $m = 6$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

Figure 7.8 demonstrates that utilization is higher when the number of the reserved channels is lower. PNCQ_GC with $h = 8$ has lowest utilization as it reserves the highest number channels for handoff calls.

To conclude, it is vital to choose an optimal number of reserved channels since under reservation can result in high CDP, while over reservation can result in high CRP, CBP and low utilization.

7.2.3 Impact of the queue length

Now we look at the effects of varying queue length on the system performance. PNCQ_GC schemes which have queue lengths of 1, 6 and 11, with $n = 20$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$ are investigated.

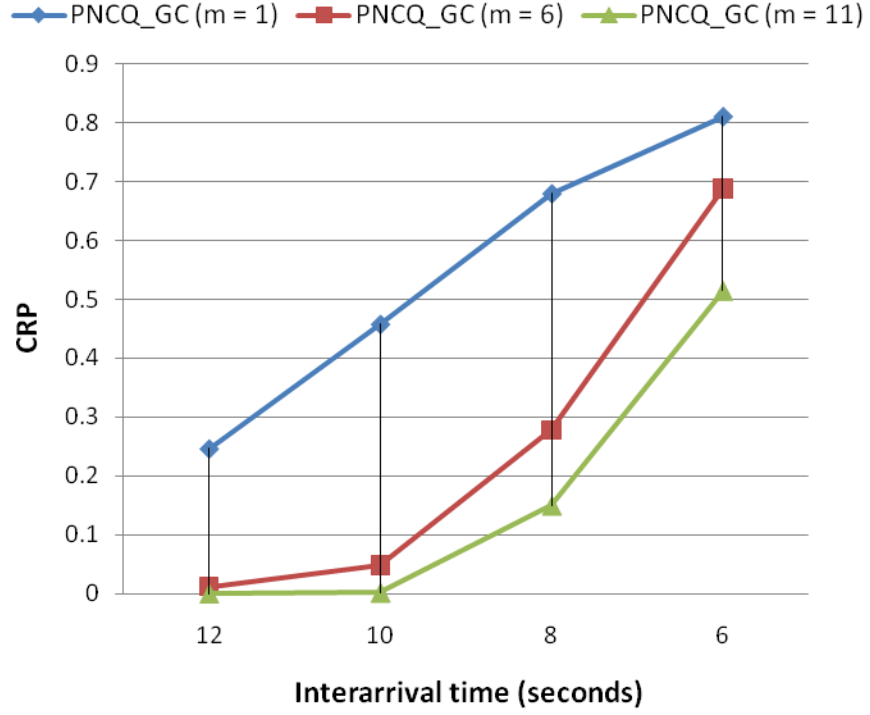


Figure 7.9: CRP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

Figure 7.9 and 7.10 indicate that the higher the queue length is, the lower the values of CRP and CBP are, as more new calls are queued. This in turn, results in a lower number of reattempts. Hence, PNCQ_GC with $m = 11$ has the lowest CRP and CBP values.

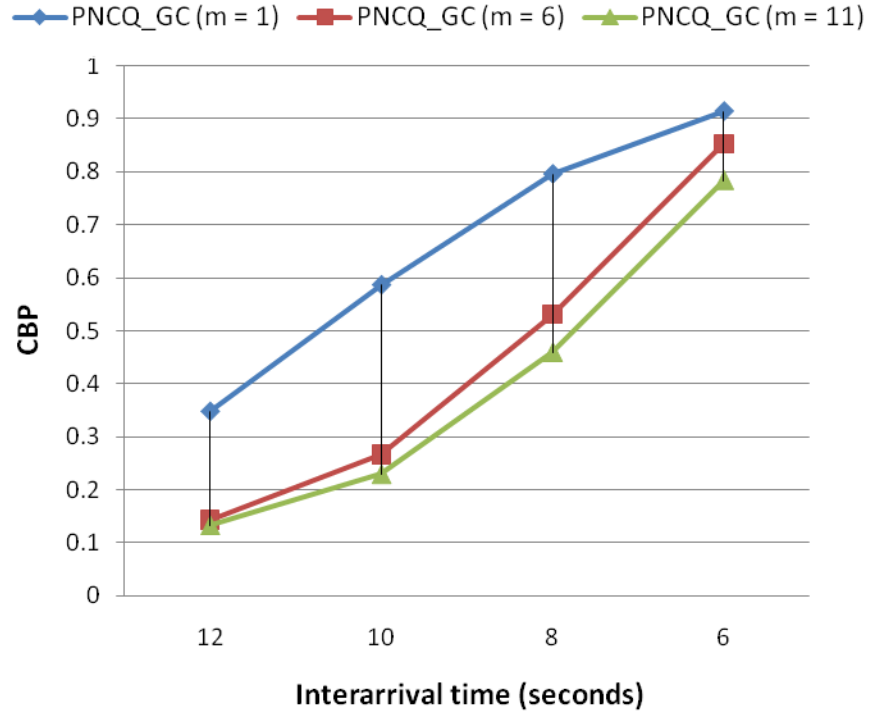


Figure 7.10: CBP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

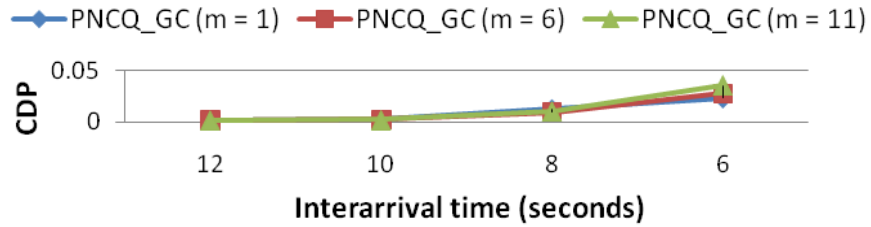


Figure 7.11: CDP versus interarrival time for PNCQ_GC scheme for various m values with $n = 20$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

Figure 7.11 and 7.12 show that CDP and utilization are not affected by the change in the queue length, since the number of reserved channels is unvarying.

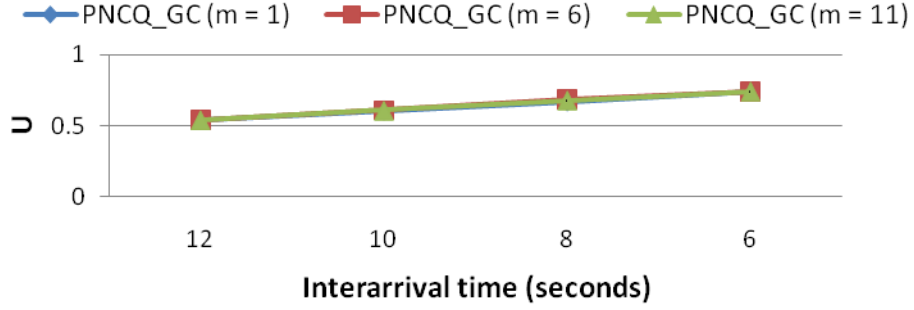


Figure 7.12: Utilization versus interarrival time for PNCQ_GC scheme for various m values with $n = 20$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 1.0$ and $\delta = 0.8$.

In conclusion, queue length is an important factor for the PNCQ policy, and an insufficient queue results in drastically high CRP and CBP.

7.2.4 Impact of the queuing threshold

Next, we consider how the PNCQ_GC scheme behaves when the number of new calls with remaining time below the queuing threshold varies. This will show the importance of choosing the optimal queuing threshold. PNCQ_GC schemes with various β values and $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$, $\gamma = 1.0$, $\delta = 0.8$ are considered.

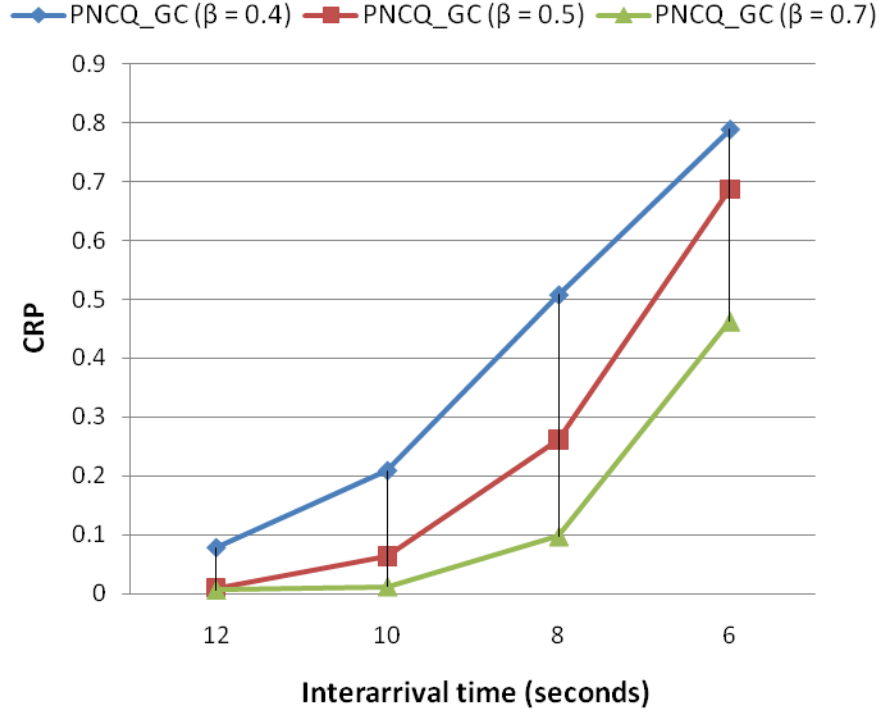


Figure 7.13: CRP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$, $\gamma = 1.0$ and $\delta = 0.8$.

As depicted in Figure 7.12 and 7.13, the values of CRP and CBP are increasing as β decreases. That is caused by the increasing number of calls with high remaining times, which results in an increasing number of reattempts. PNCQ_GC scheme with $\beta = 0.7$ has the lowest CRP and CBP values as it assumes that only 30% of calls have remaining times above the queuing threshold.

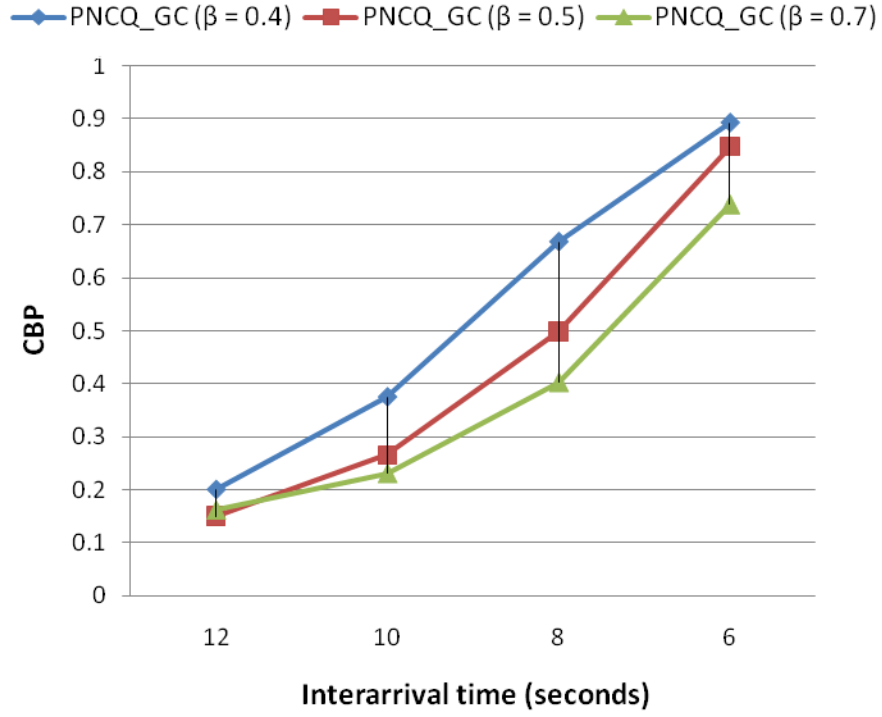


Figure 7.14: CBP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$, $\gamma = 1.0$ and $\delta = 0.8$.

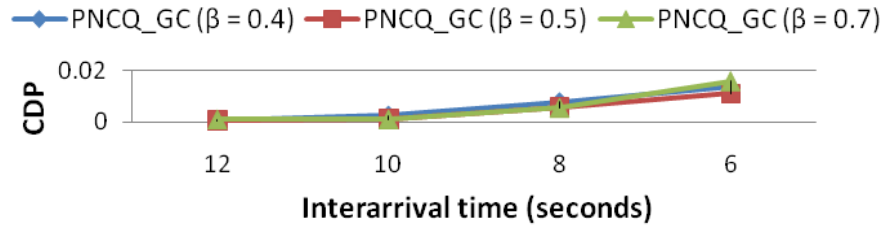


Figure 7.15: CDP versus interarrival time for PNCQ_GC scheme for various β values with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$, $\gamma = 1.0$ and $\delta = 0.8$.

Figures 7.5 and 7.16 show that once again, CDP and utilization are not affected since handoff conditions and channel allocation are not changing.

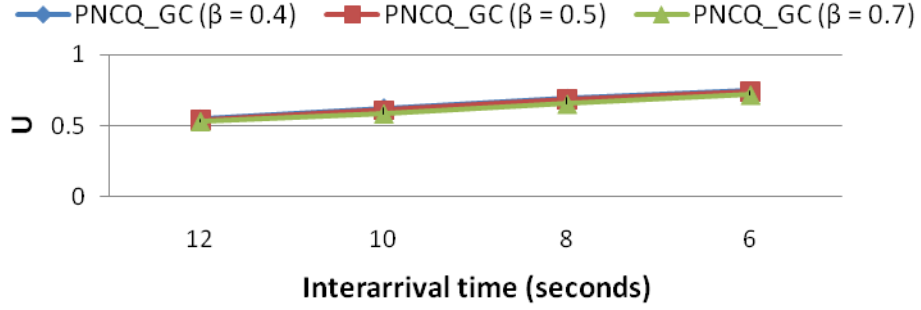


Figure 7.16: Utilization versus interarrival time for PNCQ_GC scheme for various β values with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$, $\gamma = 1.0$ and $\delta = 0.8$.

To summarize, it is important to select a queuing threshold which will allow only calls with high remaining times to be queued, otherwise the percentage of calls with remaining time above the threshold will increase, thus resulting in high CRP and CBP. This is due to the fact that more calls will expect to be queued.

7.2.5 Impact of the varying traffic conditions

We finalize the performance evaluation of the PNCQ_GC scheme by inspecting its performance under various traffic conditions. In the first scenario, which is PNCQ_GC (0.5/0.25/0.25), voice, data and video calls constitute 50%, 25% and 25% of all the generated calls, respectively. In the second scenario, which is PNCQ_GC (0.7/0.2/0.1), the percentage of voice calls is increased to 70%, and the percentage of data and video calls are reduced to 20% and 10%, respectively.

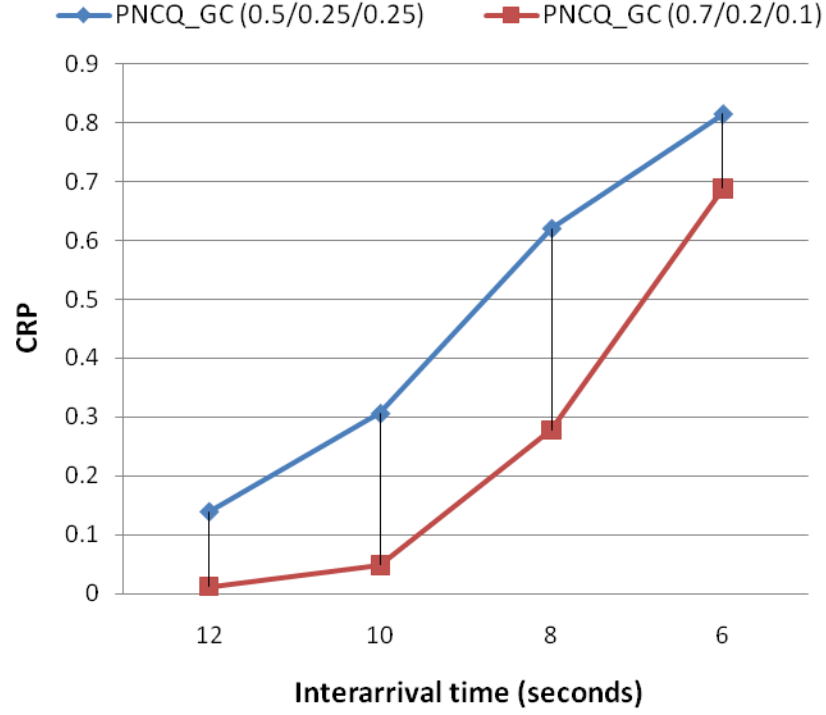


Figure 7.17: CRP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$ and $\gamma = 1.0$.

In Figure 7.17 and 7.18, it is seen that PNCQ_GC (0.5/0.25/0.25) has higher CRP and CBP than PNCQ_GC (0.7/0.2/0.1) because it generates a higher percentage of video and data calls, which require more number of channels than voice calls. Hence, the system runs out of channels faster, compared to the scenario in which there are more voice calls.

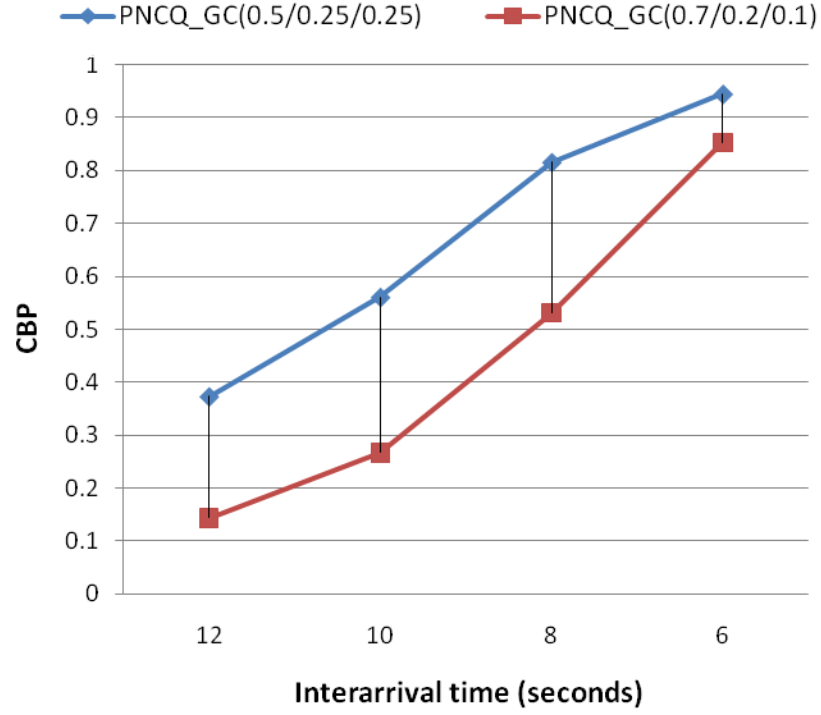


Figure 7.18: CBP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$ and $\gamma = 1.0$.

Figure 7.19 shows that CDP is negatively affected by the heavy traffic. This is because reserved channels are consumed faster when the percentage of video and data calls increase, as they require more channels.

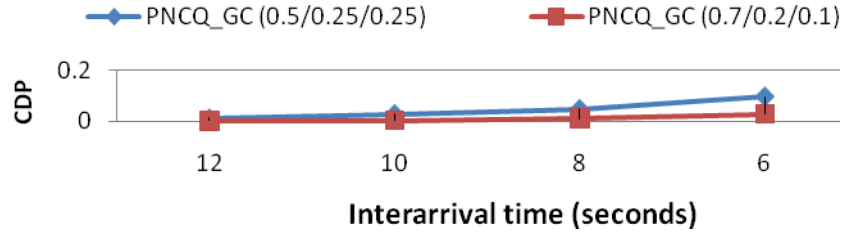


Figure 7.19: CDP versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$ and $\gamma = 1.0$.

On the other hand, Figure 7.20 indicates that the system utilization is higher under heavier traffic. The reason for this is that channels get occupied faster under heavier load, as data and video calls have higher channel requirements.

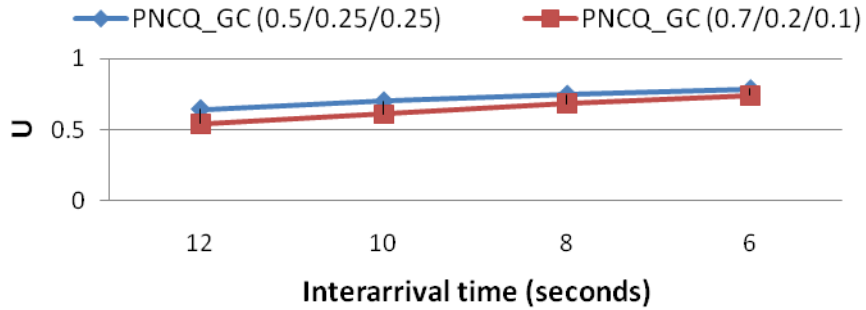


Figure 7.20: Utilization versus interarrival time for PNCQ_GC scheme for varying traffic conditions (voice/video/data) with $n = 20$, $h = 8$, $m = 6$, $\alpha = 0.3$ and $\gamma = 1.0$.

7.3 Comparison of PNCQ_GC and SNCQ_GC schemes

In this section, we compare the performances of the PNCQ_GC and the SNCQ_GC schemes under three different scenarios.

7.3.1 Case 1: $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$

Firstly, we compare the performance of the PNCQ_GC and the SNCQ_GC schemes with parameters set as follows: $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

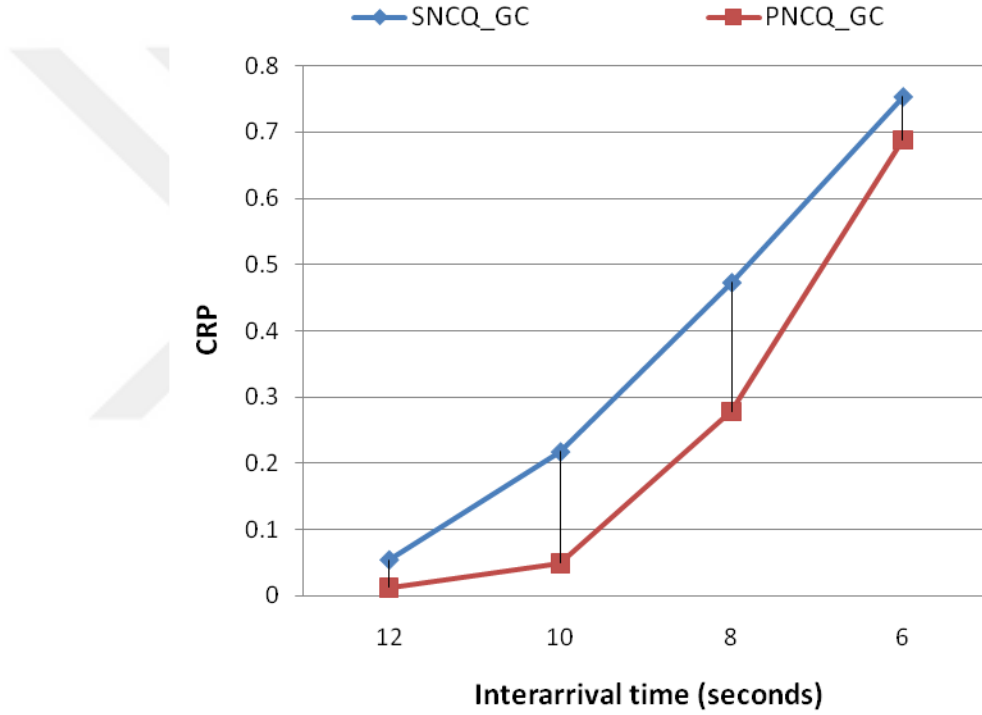


Figure 7.21: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with

$n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

By examining Figures 7.21 and 7.22 it can be seen that the PNCQ_GC scheme achieves radically lower CRP and CBP values compared to the SNCQ_GC scheme.

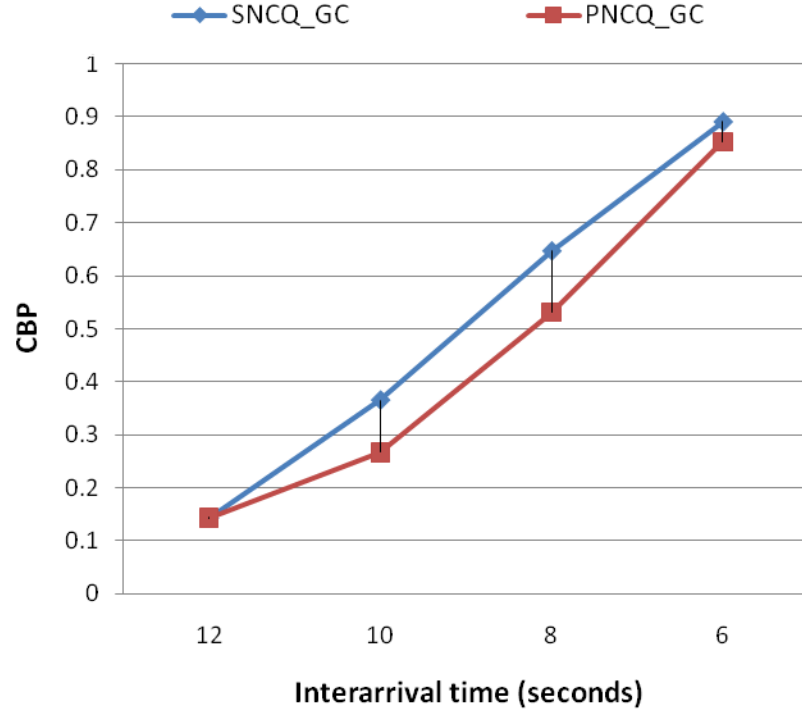


Figure 7.22: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$.

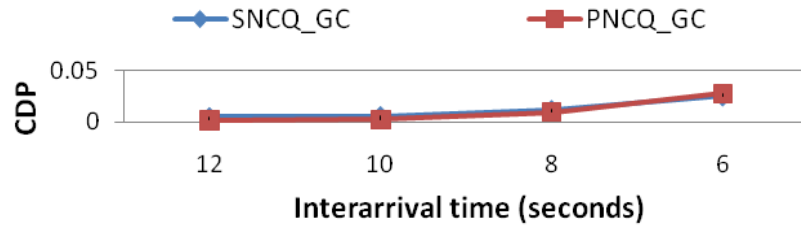


Figure 7.23: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20, m = 6, h = 8, \alpha = 0.3, \beta = 0.5, \delta = 0.8$ and $\gamma = 1.0$.

Figures 7.23 indicates that the PNCQ_GC scheme produces a low CDP, similar to the CDP of the SNCQ_GC scheme.

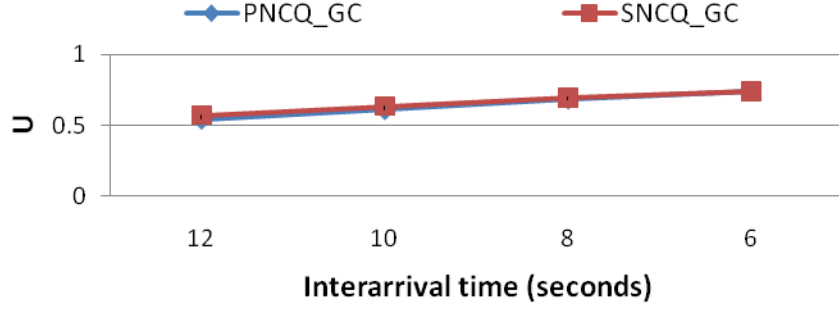


Figure 7.24: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes

with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

As depicted in Figure 7.24, the system utilization of the PNCQ_GC scheme is as high as the system utilization of the SNCQ_GC scheme.

7.3.2 Case 2: $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$

We continue, by comparing the performances of the PNCQ_GC and the SNCQ_GC schemes under the scenario of a very limited queue capacity, with $m = 1$. The rest of the parameters are set as follows: $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

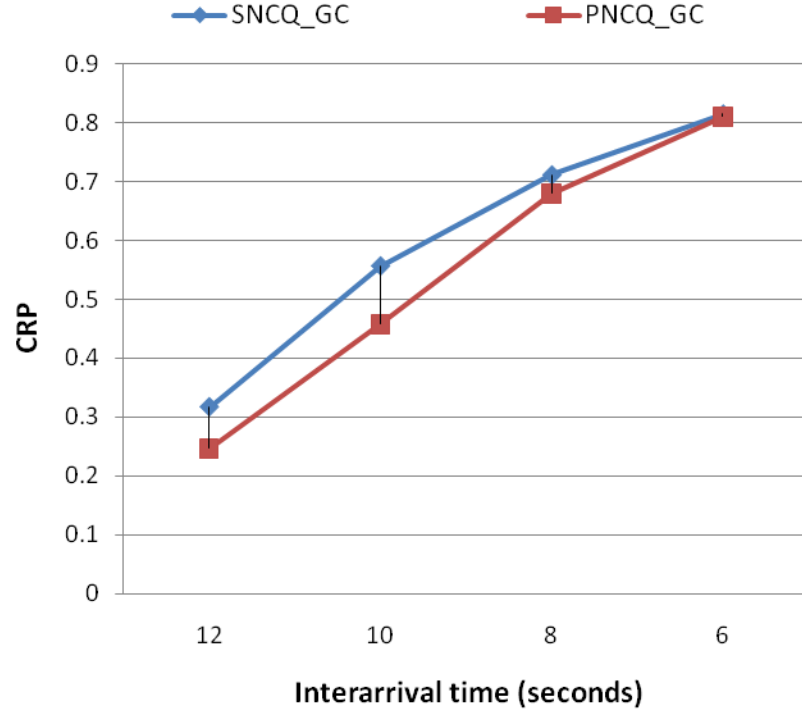


Figure 7.25: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

Even in this scenario, with a very limited queue capacity ($m = 1$), the PNCQ_GC scheme outperforms the SNCQ_GC scheme in terms of CRP and CBP, as illustrated in Figures 7.25 and 7.26.

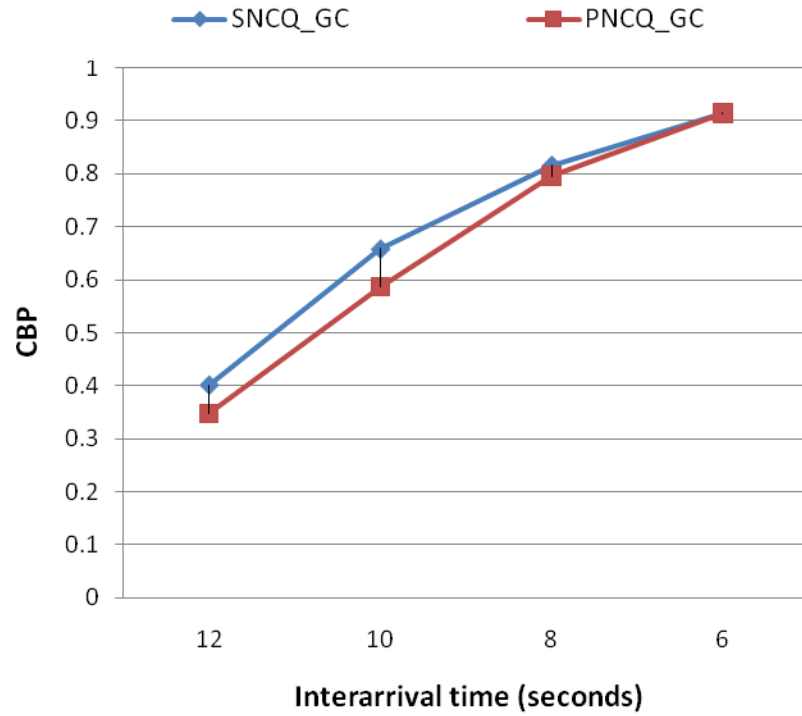


Figure 7.26: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

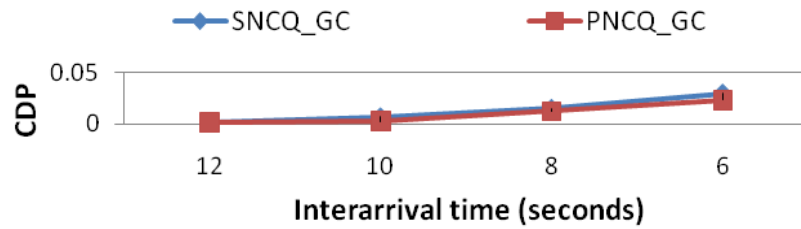


Figure 7.27: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes with $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

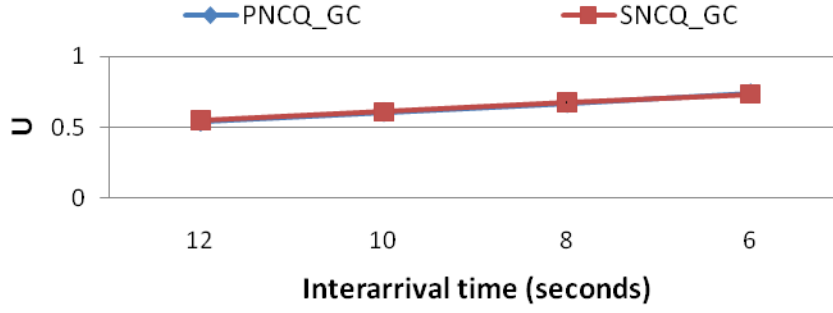


Figure 7.28: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes

with $n = 20$, $m = 1$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.8$ and $\gamma = 1.0$.

Figures 7.27 and 7.28 show that CDP and utilization are once again the same for both schemes.

7.3.3 Case 3: $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$

Finally, the PNCQ_GC and the SNCQ_GC schemes are compared under heavy traffic load with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$. In this scenario, voice, video and data calls constitute 50%, 25% and 25% of the traffic in the cell, respectively.

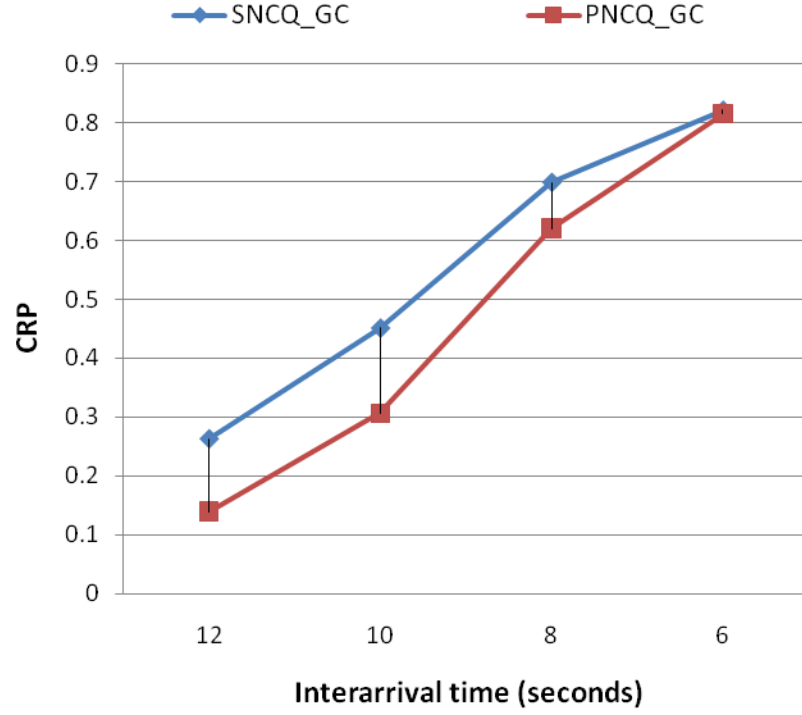


Figure 7.29: CRP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$.

Figures 7.29 and 7.30 show that even under heavy traffic load, the PNCQ_GC scheme achieves better results than the SNCQ_GC scheme in terms of CRP and CBP.

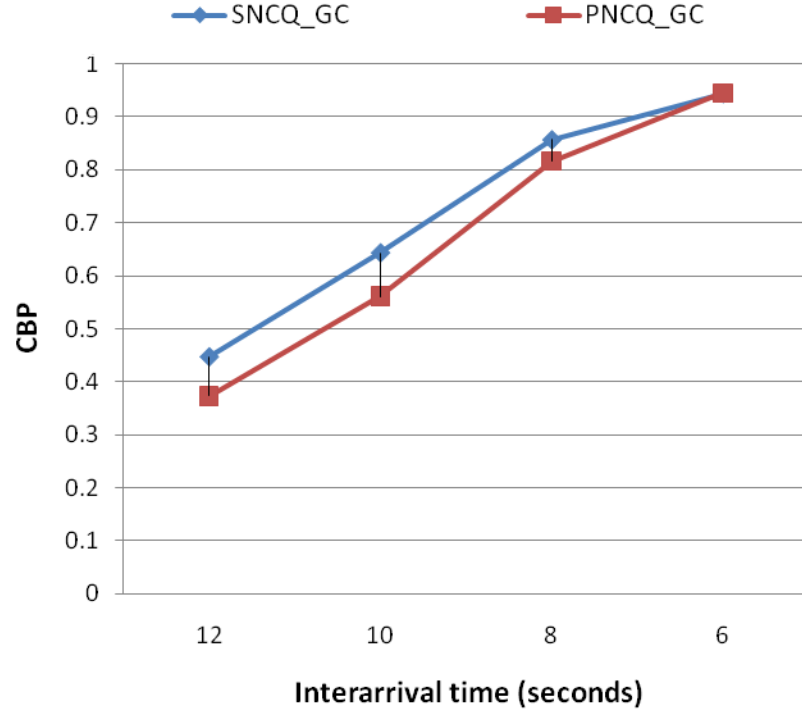


Figure 7.30: CBP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$.

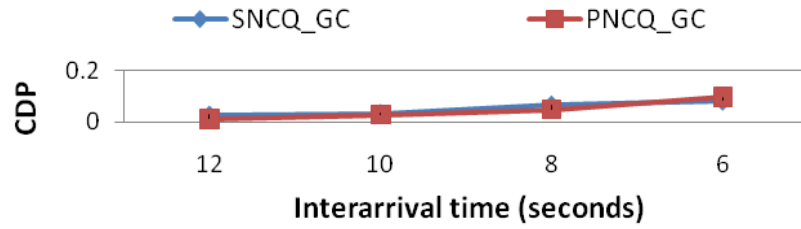


Figure 7.31: CDP versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$.

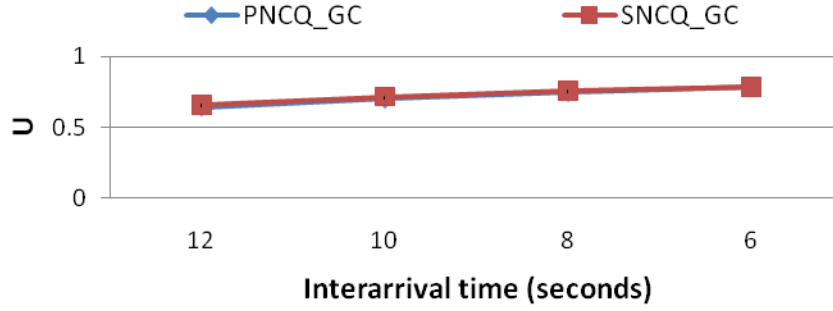


Figure 7.32: Utilization versus interarrival time for PNCQ_GC and SNCQ_GC schemes under heavy traffic load with $n = 20$, $m = 6$, $h = 8$, $\alpha = 0.3$, $\beta = 0.5$, $\delta = 0.75$ and $\gamma = 1.0$.

As depicted in figures 7.31 and 7.32, CDP and utilization of the PNCQ_GC and the SNCQ_GC schemes are similar.

7.3.4 Overview

To sum up, the PNCQ_GC scheme significantly outperforms SNCQ_GC scheme in terms of CRP and CBP under various conditions. This is because the PNCQ_GC scheme allows queuing of new calls with high remaining time only, as they produce a higher number of connection reattempts, while the SNCQ_GC scheme allows queuing of all new calls.

Moreover, the PNCQ_GC scheme does not compromise in term of CDP and system utilization. The CDP of the PNCQ_GC scheme is as low as CDP of the SNCQ_GC scheme and utilization is as high as the utilization of the SNCQ_GC scheme under various conditions. The reason for that is that the number of the reserved handoff channels was kept the same for both schemes.

Chapter 8

CONCLUSION

In this thesis, we developed a novel classification of Call Admission Control schemes in wireless cellular networks. We provided a wide-ranging review of the work done in the field of handoff prioritization and user mobility prediction. From our research, we can conclude that future Call Admission Control schemes should have low computation and/or implementation complexity, be efficient, provide support for multimedia traffic, consider cells of irregular shapes and sizes, and have low signaling overhead.

The classification offered in this thesis is targeted at both academia and industry, as it aims to discuss the state-of-the-art in Call Admission Control in wireless cellular networks. Care was taken to make sure that no important scheme was omitted from these discussions, and as such, the classification in this thesis can serve as a pivotal reference material for those interested in this area of research. The proposed classification is significant in that, currently, there is no other such classification effort that has been published, to the best of our knowledge.

In this thesis, we also introduced a Prioritized New Call Queuing mechanism for Call Admission Control schemes that prioritize handoffs over new calls. The proposed policy improves the performance of the system by reducing the number of connection reattempts as they are known to have a negative impact on the system performance. The Prioritized New Call Queuing mechanism can be combined with any handoff

prioritizing Call Admission Control scheme in order to improve the performance of new calls.

The simulation results show that, compared to the conventionally employed simple new call queuing policy, the prioritized new call queuing approach achieves considerably better results in terms of new call blocking and reattempt probabilities while keeping the same low handoff dropping probability and high system utilization.

The proposed scheme is suitable for real-life and future cellular networks as it deals with real-time and non real-time traffic, considers new call reattempts and termination of new calls due to user impatience. Moreover, it does not suffer from high computation and implementation complexities. However, it was assumed that voice, data and video calls follows the same reattempt model, which is not true for real life cellular networks. The reattempt model used for PNCQ policy is more suitable for voice calls only. Therefore, as future work, we will develop reattempt models suitable for data and video traffic. Moreover, New Call Queuing policy will be extended to include stationary mobile users. Such calls will be always queued without calculating the remaining time.

Finally, we are planning to develop a multiple threshold channel reservation scheme which is based on the concept of queuing threshold used in the Prioritized New Call Queuing policy. In this approach, MSs with different remaining time will have different thresholds.

REFERENCES

- [1] V. Abdulova and I. Aybay, Handoff prioritizing schemes in cellular wireless networks, in: Proceedings International Symposium on Computer Networks (June 2006) 79–84.
- [2] A. Abutaleb and V.O.K. Li, Performance evaluation of handoff schemes in personal communication systems, IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences E78-A (July 1995) 773–784.
- [3] A. Aljadhari and T. Znati, Predictive mobility support for QoS provisioning in mobile wireless environments, IEEE Journal on Selected Areas in Communications 19 (October 2001) 1915–1930.
- [4] D. Ashbrook and T. Starner, Learning significant locations and predicting user movement with GPS, in: Proceedings International Symposium on Wearable Computers (October 2002) 101–108.
- [5] V. Bharghavan, and M. Jayanth, Profile-based next-cell prediction in indoor wireless LAN, in: Proceedings IEEE SICON (April 1997).

- [6] A. Bhattacharya and S.K. Das, LeZi—Update: an information-theoretic approach to track mobile users in PCS networks, *ACM Wireless Networks* 8 (March 2002) 121–135.
- [7] E. Cayirci and I.F. Akyildiz, User mobility pattern scheme for location update and paging in wireless systems, *IEEE Transactions on Mobile Computing* 1 (July-September 2002) 236–247.
- [8] J. Chan and A. Seneviratne, A practical user mobility prediction algorithm for supporting adaptive QoS in wireless Networks, in: *Proceedings IEEE International Conference on Networks* (September 1999) 104–111.
- [9] R.-S. Chang and S.-J. Leu, Handoff ordering using signal strength for multimedia communications in wireless networks, *IEEE Transactions on Wireless Communications* 3 (September 2004) 1526–1532.
- [10] C. Chen, S. Kumar, and C.-C. J. Kuo, Dynamic call admission control scheme for QoS priority handoff in multimedia cellular systems, in: *Proceedings Wireless Communications and Networking Conference* (March, 2002) 114–118.
- [11] X. Chen, B. Li, and Y. Fang, A dynamic multiple-threshold bandwidth reservation (DMTBR) scheme for QoS provisioning in multimedia wireless networks, *IEEE Transactions on Wireless Communications* 4 (March 2005) 583–592.

- [12] M.-H. Chiu and M. A. Bassiouni, Predictive scheme for handoff prioritization in cellular networks based on mobile positioning, *IEEE Journal on Selected Areas in Communications* 18 (March 2000) 510–522.
- [13] C.H. Choi and S.J. Kim, A call admission control mechanism using mobility graph in mobile multimedia networks, *Wireless personal Communications* 25 (July 2003) 321–341.
- [14] C. Choi, M. Kim and S. Kim, Call admission control using the moving pattern of mobile user for mobile multimedia networks, in: *Proceedings IEEE Conference on Local Computer Networks* (November 2002) 431–440.
- [15] S. Choi K. Shin, Adaptive bandwidth reservation and admission control in QoS-sensitive cellular networks, *IEEE Transactions on Parallel and Distributed Systems* 13 (September 2002) 882–897.
- [16] J. Diederich and M. Zitterbart, A simple and scalable handoff prioritization scheme, *Computer Communications* 28 (May 2005) 773–789.
- [17] H. G. Ebersman and O. K. Tonguz, Handoff ordering using signal prediction priority queuing in personal communication system, *IEEE Transactions on Vehicular Technology* 48 (January 1999) 20–35.

- [18] M. El-Kadi, S. Olariu, and H. A. Wahab, A rate-based borrowing scheme for QoS provisioning in multimedia wireless networks, *IEEE Transactions on Parallel and Distributed Systems* 13 (February 2002) 156–166.
- [19] B. M. Epstein and M. Schwartz, Reservation strategies for multimedia traffic in a wireless environment, in: *Proceedings IEEE Vehicular Technology Conference* (July 1995) 165–169.
- [20] B. M. Epstein and M. Schwartz, Predictive QoS-based admission control for multiclass traffic in cellular wireless networks, *IEEE Journal on Selected Areas in Communications* 18 (March 2000) 523–534.
- [21] Y.-R. Haung, Y.-B. Lin, and J. M. Ho, Performance analysis for voice/data integration on a finite mobile systems, *IEEE Transactions on Vehicular Technology* 49 (March 2000) 367–378.
- [22] D. Hong and S. S. Rappaport, Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures, *IEEE Transactions on Vehicular Technology* 35 (August 1986) 77–92.

- [23] D. Hong and S. S. Rappaport, Priority oriented channels access for cellular systems serving vehicular and portable radio telephones, in: Proceedings I Communications, Speech and Vision 136 (October 1989) 339–346.
- [24] F. Hu and N. K. Sharma, Priority-determined multiclass handoff scheme with guaranteed mobile QoS in wireless multimedia networks, IEEE Transaction on Vehicular Technology 53 (January 2004) 118–135.
- [25] L. Huang, S. Kumar and C.-C. J. Kuo, Adaptive resource allocation for multimedia QoS management in wireless networks, IEEE Transaction on Vehicular Technology 53 (March 2004) 547–558.
- [26] M. M. Islam and M. Murshed, Novel velocity and call duration support for QoS provision in mobile wireless networks, IEEE Transactions on Wireless Communications 11 (October 2004) 22–30.
- [27] M.M. Islam and M. Murshed, Parametric mobility support dynamic resource reservation and call admission control scheme for cellular multimedia communications, Computer Communications 30 (January 2007) 233–248.
- [28] A. Jayasuriya and J. Asenstorfer, Mobility prediction for cellular networks based on the observed traffic patterns, in: Proceedings IASTED International Conference on Wireless and Optical Communications (July 2002) 356–235.

- [29] I. Katzela and M. Naghshineh, Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey, *IEEE Personal Communications* 3 (June 1996) 10–31.
- [30] H. Kim and J. Jung, A mobility prediction handover algorithm for effective channel assignment in wireless ATM, in: *Proceedings Global Telecommunications Conference* (November 2001) 3673–3680.
- [31] B. Kraimeche and M. Schwartz, Analysis of traffic access control strategies in integrated service networks, *IEEE Transactions on Communications* (October 1985) 1085–1093.
- [32] B. Kraimeche and M. Schwartz, Bandwidth allocation strategies in wide-band integrated networks, *IEEE Journal on Selected Areas in Communications* 4 (September 1986) 869–878.
- [33] B. Kraimeche and M. Schwartz, A channel access structure for wideband ISDN, *IEEE Journal on Selected Areas in Communications* 5 (October 1987) 1327–1335.
- [34] V. Kumar and P. Venkataram, A prediction based location management using multi-layer neural networks, *Journal of the Indian Institute of Science* 82 (2002) 7–21.

- [35] J. Y. Lee, J.-G. Choi, K. Park, and S. Bahk, Realistic cell-oriented adaptive admission control for QoS support in wireless multimedia networks, *IEEE Transaction on Vehicular Technology* 52 (May 2003) 512–524.
- [36] D.-S. Lee and Y.-H. Hsueh, Bandwidth-reservation scheme based on road information for next-generation cellular networks, *IEEE Transaction on Vehicular Technology* 53 (January 2004) 243–252.
- [37] D. A. Levine, I. F. Akyildiz, and M. Naghshineh, A resource estimation and call admission algorithm for wireless multimedia networks using the shadow cluster concept, *IEEE/ACM Transactions on Networking* 5 (February 1997) 1–12.
- [38] W. Li, H. Chen, and D. P. Agrawal, Performance analysis of handoff schemes with preemptive and nonpreemptive channel borrowing in integrated wireless cellular networks, *IEEE Transactions on Wireless Communications* 4 (May 2005) 1222–1233.
- [39] B. Li, L. Li, B. Li, and X. Cao, On handoff performance for and integrated voice/data cellular system, *Wireless Networks* 9 (July 2003) 393–402.
- [40] B. Li, C. Lin, and S. T. Chanson, Analysis of a hybrid cutoff priority scheme for multiple classes of traffic in multimedia wireless networks, *Wireless Networks* 4 (July 1998) 279–290.

- [41] B. Liang and Z.J. Haas, Predictive distance-based mobility management for multidimensional PCS networks, *IEEE/ACM Trans. Networking* 11 (October 2003) 714–732.
- [42] T. Liu, P. Bahl, and I. Chlamtac, Mobility modeling, location tracking, and trajectory prediction in wireless ATM networks, *IEEE Journal on Selected Areas in Communications* 16 (August 1998) 922–936.
- [43] G. Liu and G. Maguire, A predictive mobility management algorithm for wireless mobile computing and communications, in: *Proceedings IEEE International Conference* (November 1995) 268–272.
- [44] G. Liu and G. Maguire, A class of mobile motion prediction algorithms for wireless mobile computing and communication, *ACM International Journal on Wireless Networks* 1, (June 1996) 113–121.
- [45] S. Lu and V. Bharghavan, Adaptive resource management algorithms for indoor mobile computing environment, in *Proceedings: ACM SIGCOMM* (September 1996) 231–242.
- [46] L.-L. Lu, J.-L.C. Wu and H.-H. Liu, Mobility-aided adaptive resource reservation schemes in wireless multimedia networks, *Computer and Electrical Engineering* 32 (January-May 2006) 102–117.

- [47] N. Marmasse and C. Schmandt, A user-centered location model, *Personal and Ubiquitous Computing* 6 (December 2002) 318–321.
- [48] M. Naghshineh and M. Schwartz, Distributed call admission control in mobile/wireless networks, *IEEE Journal on Selected Areas in Communications* 14 (May 1996) 711–717.
- [49] S.-H. Oh and D.-W. Tcha, Prioritized channel assignment in a cellular radio network, *IEEE Transactions on Communications* 40 (July 1992) 1259–1269.
- [50] C. Oliveira, J. B. Kim, and T. Suda, An adaptive bandwidth reservation scheme for high-speed multimedia wireless networks, *IEEE Journal on Selected Areas in Communications* 16 (August 1998) 858–874.
- [51] F. N. Pavlidou, Two-dimensional traffic models for cellular mobile systems, *IEEE Transactions on Communications* 42 (February/March/April 1994) 1505–1511.
- [52] C. Purzynski and S. S. Rappaport, Multiple call handoff problem with queued handoffs and mixed platform types, *IEE Proceedings on Communications* 142, (February 1995) 31–39.

- [53] P. Ramanathan, K. M. Sivalingam, P. Agrawal, and S. Kishore, Dynamic resource allocation schemes during handoff for mobile multimedia wireless networks, *IEEE Journal on Selected Areas in Communications* (17) (July 1999) 1270–1283.
- [54] T.S. Rappaport, J.H. Reed and B.D. Woerner, Position location using wireless communications on highways of the future, *IEEE Communications Magazine* 34 (October 1996) 33–41.
- [55] S. Rashad, M. Kantardzic and A. Kumar, User mobility oriented predictive call admission control and resource reservation for next-generation mobile networks, *Journal of Parallel and Distributed Computing* 66 (July 2006) 971–988.
- [56] I. Rubin and J. K. Lee, Performance of integrated data/voice circuit-switched multi-access communications channels, in: *Proceedings Global Telecommunications Conference* (November 1988) 506–510.
- [57] N. Samaan and A. Karmouch, A mobility prediction architecture based on contextual knowledge and spatial conceptual maps, *IEEE Transactions on Mobile Computing* 4 (November 2005) 537–551.
- [58] B. Schmidt-Belz, M. Makelainen, A. Nick, and S. Poslad, Intelligent brokering of tourism services for mobile users, in: *Proceedings International Conference by Federation on Information Technology in Tourism* (January 2002).

- [59] X. Shen, J. W. Mark and J. Ye, User mobility profile prediction: an adaptive fuzzy inference approach, *Wireless Networks* 6 (November 2000) 363–374.
- [60] W.-S. Soh and H.S. Kim, Dynamic guard bandwidth scheme for wireless broadband networks, in *Proceedings: IEEE INFOCOM* (April 2001) 572–581.
- [61] W.S. Soh and H.S. Kim, QOS provisioning in cellular networks based on mobility prediction techniques, *IEEE Communications Magazine* 41 (January 2003) 86–92.
- [62] W.-S. Soh and H.S. Kim, A predictive bandwidth reservation scheme using mobile positioning and road topology information, *IEEE/ACM Transactions on Networking* 14 (October 2006) 1078–1091.
- [63] M.S. Sricharan, V. Vaidehi and P.P. Arun, An activity based mobility prediction strategy for next generation wireless networks, in: *Proceedings Conference on Wireless and Optical Communications Networks* (April 2006).
- [64] S. Tabbane, An alternative strategy for location tracking, *IEEE Journal on Selected Areas in Communications* 13 (June 1995) 880–892.
- [65] S. Tekinay and B. Jabbari, Handover and channel assignment in mobile cellular networks, *IEEE Communications Magazine* 29 (November 1991) 42–46.

- [66] S. Tekinay and B. Jabbari, A measurement-based prioritization scheme for handovers in mobile cellular networks, *IEEE Journal on Selected Areas in Communications* 10 (October 1992) 1343–1350.
- [67] B. Tolg and W. Bziuk, A new topology-based algorithm for next cell prediction in cellular networks, in: *Proceedings Global Telecommunications Conference 2* (December 2003) 919–923.
- [68] J. Tsiligaridis and R. Acharya, A clustering prediction scheme for wireless cellular network, in *Proceedings: International Symposium on Collaborative Technologies and Systems* (May 2005) 298–304.
- [69] K. Wang, J.-M. Liao and J.-M. Chen, Intelligent location tracking strategy in PCS, *IEE Proceedings on Communications* 147 (February 2000) 63–68.
- [70] J. Wang, Q.-A. Zeng, and D. P. Agrawal, Performance analysis of a preemptive and priority reservation handoff scheme for integrated service-based wireless mobile networks, *IEEE Transactions on Mobile Computing* 2 (January 2003) 65–75.
- [71] Y. Wei, C. Lin, F. Ren, R. Raad and E. Dutkiewicz, Dynamic handoff scheme in differentiated QoS wireless multimedia networks, *Computer Communications* 27 (June 2004) 1001-1011.

- [72] H.-K. Wu, M.-H. Jin, J.-T. Horng, C.-Y. Ke, Personal paging area design based on mobile's moving behaviors, in: Proceedings IEEE Conference on Computer and Communications (April 2001) 21–30.
- [73] Z. Xu, Z. Ye, S. Krishnamurthy, S. Tripathi and M. Molle, A New Adaptive Channel Reservation Scheme for Handoff Calls in Wireless Cellular Networks, Lecture Notes In Computer Science 2345 (2002) 672–684.
- [74] W.-B. Yang and E. Geraniotis, Admission policies for integrated voice and data traffic in CDMA packet radio networks, IEEE Journal on Selected Areas in Communications 12 (May 1994) 654–664.
- [75] G. Yavas, D. Katsaros, O. Ulusoy and Y. Manolopoulos, A data mining approach for location prediction in mobile environments, Data and Knowledge Engineering 54 (August 2005) 121 – 146.
- [76] F. Yu and V. Leung, Mobility-based predictive call admission control and bandwidth reservation in wireless cellular networks, Computer Networks 38 (April 2002) 577–589.
- [77] R. Zander and J.M. Karlsson, Predictive and adaptive resource reservation (PARR) for cellular networks, International Journal of Wireless Information Networks 11 (July 2004) 161–171.

- [78] H. Sasaoka (2001). Mobile Communications. Amsterdam, The Netherlands: IOS Press.
- [79] K. Nakano, K. Saita, M. Sengoku, Y. Yamada and S. Shinoda, Mobile Communication Traffic Analysis on a Road Systems Model, in Proceedings: Performance and Management of Complex Communication Networks (November 1997) 3-20.
- [80] K. Saita, K. Nakano, M. Sengoku and Y. Yamada, An Analysis of Communication Traffic Characteristics in Cellular Mobile Systems Using a Road Systems Model, in Proceedings: IEICE General Conference (1997) 552.
- [81] K. Nakano, K. Saita, N. Karasawa, M. Sengoku and S. Shinoda, Teletraffic Characteristics in Cellular Systems and Traffic Flow in Road Systems, in Proceedings: IEEE 49th Vehicular Technology Conference (May 1999) 1193-1197.
- [82] S. Malomsoky and A. Szlavik, Mobility and Traffic Analysis for WCDMA Networks, in Proceedings: International Conference on the Performance and QoS of Next Generation Networking (November 2000), 187-208.
- [83] J. Biesterfeld, E. Ennigrou, K. Jobmann, Location Prediction in Mobile Networks with Neural Networks, in Proceedings: International Workshop on Applications of Neural Networks to Telecommunications (Jun 1997) 207-214.

- [84] S-C. Liou and H-C. Lu, Applied neural network for location prediction and resources reservation scheme in wireless networks, in Proceedings: International Conference on Communication Technology (April 2003) 958-961.
- [85] J. Capka and R. Boutaba, Mobility prediction in wireless networks using neural networks, Lecture Notes on Computer Science 3271 (2004) 320-333.
- [86] J.M. Franois and G. Leduc, Entropy-based knowledge spreading and application to mobility prediction, in Proceedings: ACM Conference on Emerging Network Experiment and Technology (2005) 10–20.
- [87] M. Daouia, A. M'zoughib, M. Lalama, M. Belkadia and R. Aoudjita, Mobility prediction based on an ant system, Computer Communications 31 (April 2008) 3090-3097.
- [88] J. Scourias, T. Kunz, An activity-based mobility model and location management simulation framework, in Proceedings: ACM Int. Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (1999) 61–68.
- [89] O. Spaniol, Mobility Management in GPRS, Seminar: Data Communication and Distributed System, (Winter 2003/04).

- [90] M. Zonoozi and P. Dassanayake, User Mobility Modeling and Characterization of Mobility Patterns, *Journal on Selected Areas in Communications* 15 (September 1997) 1239-1252.
- [91] K. Saitoh, H. Hidaka, N. Shinagawa, T. Kobayashi, Vehicle motion in Large and Small Cities and Teletraffic Characterization in Cellular Communication Systems, *IEICE Transactions on Communications* 84 (April 2001) 805-813.
- [92] K. Saitoh, H. Hidaka, N. Shinagawa, T. Kobayashi, Teletraffic Characteristics of Cellular Communication for Different Types of Vehicle Motion, *IEICE Transactions on Communications* 84 (March 2001) 558-565.
- [93] T. Kobayashi, N. Shinagawa, and Y. Watanabe, Vehicle mobility characterization based on measurements and its application to cellular communication systems, *IEICE Transactions on Communications* 82 (December 1999) 2055-2060.
- [94] D. Tang and M. Baker, Analysis of a Metropolitan-Area Wireless Network, *Wireless Networks* 8 (March-May 2002) 107-120.
- [95] S. Thajchayapong and J. M. Peha, Mobility Patterns in Microcellular Wireless Networks, in *Proceedings: Wireless Communications and Networking Conference* (March 2003).

- [96] B. Fan and A. Helmy. Wireless Ad Hoc and Sensor Networks, A Survey of Mobility Models in Wireless Adhoc Networks, Kluwer Academic Publishers (2004) 1-29.
- [97] J. Cowling, Dynamic Location Management in Heterogeneous Cellular Networks (2004), Bachelor Thesis, University of Sydney, Australia.
- [98] D. B. Johnson and D. A. Maltz, Dynamic source routing in ad hoc wireless networks, Mobile Computing 353 (1996) 153–181.
- [99] E. Hyttia and J. Virtamo, Random waypoint mobility model in cellular networks, Wireless Networks 13 (2007) 177-188.
- [100] K. Okada and F. Kubota, A Proposal of a Dynamic Channel Assignment Strategy with Information of Moving Direction in Micro Cellular Systems, IEICE Transactions on Fundamentals 75-A (December 1992) 1667-1673.
- [101] K. Okada, D. Park and S. Yoshimoto, A Dynamic Channel Assignment Strategy Using Information on Speed and Moving Direction for Micro Cellular Systems, IEICE Transactions on Communications 79-B (March 1996) 279-288.
- [102] P.N. Pathirana, A.V. Savkin and S.Jha, Location Estimation and Trajectory Prediction for Cellular Networks with Mobile Base Stations, IEEE Transactions on Vehicular Technology 53 (November 2004) 1903-1912.

- [103] Z. Yang and X. Wang, Joint Mobility Tracking and Handoff in Cellular Networks via Sequential Monte Carlo Filtering, *IEEE Transactions on Signal Processing* 51 (January 2003) 269-281.
- [104] X. Wang, S. Cai, H. Cheng, M. Huang and J. Cao, A Fuzzy Decision Tree Based Mobility Prediction Mechanism in Mobile Internet, *Auswireless Conference* (March 2006).
- [105] K. L. Dias, S.F.L. Fernandes and D.F.H. Sadok, Qos Provisioning in Mobile Networks Based on Aggregate Bandwidth Reservation, *Lecture Notes in Computer Science* 4742 (2007) 908–919.
- [106] V. K. N. Lau and S. V. Maric, Mobility of Queued Call Requests of a New Call-queuing Technique for Cellular Systems, *IEEE Transactions on Vehicular Technology* 47 (May 1998) 480-488.
- [107] R. A. Guerin, Queuing-blocking System with Two Arrival Streams and Guard Channels, *IEEE Transaction on Communications* 36 (1988) 153-163.
- [108] C. Chang, C. -J. Chang and K. R. Lo, Analysis of a Hierarchical Cellular System with Reneging and Dropping for Waiting New Calls and Handoff Calls, *IEEE Transactions on Vehicular Technology* 48 (July 1999) 1080-1091.

- [109] C. -J. Chang, P. -C. Huang and T. -T. Su, A Channel Borrowing Scheme in a Cellular Radio System with Guard Channels and Finite Queues, Proc. IEEE International Conference on Communications 2, (June 1996) 1168-1172.
- [110] D. McMillan, Delay Analysis of a Cellular Mobile Priority Queuing System, IEEE/ACM Transactions on Networking 3 (1995) 310-319.
- [111] P. Tran-Gia and M. Mandjes, Modeling of Customer Retrial Phenomenon, IEEE Journal on Selected Areas in Communications 15 (1997) 1406-1414.
- [112] N. Shingawa, T. Kobayashi, K. Nakano and M. Sengoku, Teletraffic Characteristics in Prioritized Hand-off Control Method Considering Reattempted Calls, IEICE Transactions on Communications E83-B (2000) 1810-1818.
- [113] M. Ajmone Marsan, G. De Carolis, E. Leonardi, R. Lo Cigno and M. Meo, An Approximate Model for the Computation of Blocking Probabilities in Cellular Networks with Repeated Calls, Springer Telecommunication Systems 15 (2000), pp. 53-62.
- [114] J. M. Gimenez-Guzman, M. J. Domenech-Benlloch, V. Pla, V. Casares-Giner and J. Martinez-Bauset, Analysis of a Cellular Network with User Redials and Automatic Handover Retrials, Lecture Notes in Computer Science 4712 (2007) 210-222.

- [115] N. Vetrivelan and A.V. Reddy, Impact and Performance Analysis of Mobility Models on Stressful Mobile WiMax Environments, International Journal of Computer and Network Security 2 (February 2010).
- [116] J. Banks, J. S. Carson II, and B. L. Nelson, Discrete-event System Simulation, Prentice Hall, 1996.
- [117] GPSS World Simulation Package:
<http://www.minutemansoftware.com/simulation.htm>.
- [118] V. Abdulova, Handoff Channel Allocation Mechanisms in Cellular Wireless Networks (2005), Master's Thesis, Eastern Mediterranean University, Northern Cyprus.
- [119] V. Abdulova and I. Aybay, Predictive Mobile-oriented Channel Reservation Schemes in Wireless Cellular Networks, Wireless Networks, Springer, accepted for publication.
- [120] V. Abdulova and I. Aybay, A Prioritized New Call Queuing Policy for Multimedia Wireless Cellular Networks, Journal of Internet Technology, Special Issue on Networks and Communications, accepted for publication.

- [121] E. Onur, H. Delic, C. Ersoy and M. U. Caglayan, Measurement-Based Replanning of GSM Cell Capacities Considering Retrials, Redials and Hand-offs, in Proceedings: IEEE ICC (2002).
- [122] E. Onur, H. Delic, C. Ersoy and M. U. Caglayan, On the Retrial and Redial Phenomena in Cellular Communication Networks, in Proceedings: IEEE WCNC (September 2000).
- [123] <http://web-html.org/ALTHOS-Wireless.Markup.Languag/8910final/LiB0002.html>
- [124] http://www.cdg.org/technology/cdma_technology/a_ross/handoff.asp



APPENDIX A: Accuracy Estimation of the Obtained Results

Using Confidence Intervals

A.1 Confidence intervals

A.1.1 Confidence interval

A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data [116]. If independent samples are taken repeatedly from the same population, and a confidence interval calculated for each sample, then a certain percentage (confidence level) of the intervals will include the unknown population parameter. Confidence intervals are usually calculated so that this percentage is 95%, but we can produce 90%, 99%, 99.9% (or whatever) confidence intervals for the unknown parameter.

The width of the confidence interval gives us some idea about how uncertain we are about the unknown parameter. A very wide interval may indicate that more data should be collected before anything very definite can be said about the parameter. Confidence intervals are more informative than the simple results of hypothesis tests since they provide a range of possible values for the unknown parameter.

A.1.2 Confidence limits

Confidence limits are the lower and upper boundaries/values of a confidence interval, that is, the values which define the range of a confidence interval [116].

The upper and lower bounds of a 95% confidence interval are the 95% confidence limits. These limits may be taken for other confidence levels, for example, 90%, 99%, 99.9%.

A.1.3 Confidence level

The confidence level is the probability value $(1-\alpha)$ associated with a confidence interval [120]. It is often expressed as a percentage. For example, say $\alpha = 0.05 = 5\%$, then the confidence level is equal to $(1-0.05) = 0.95$, i.e. a 95% confidence level.

A.1.4 Confidence interval for a mean

A confidence interval for a mean specifies a range of values within which the unknown population parameter, in this case the mean, may lie. The width of the confidence interval gives us some idea about how uncertain we are about the unknown population parameter, in this case the mean. A very wide interval may indicate that more data should be collected before anything very definite can be said about the parameter [116].

We calculate these intervals for different confidence levels, depending on how precise we want to be. We interpret an interval calculated at a 95% level as; we are 95% confident that the interval contains the true population mean. We could also say that 95% of all confidence intervals formed in this manner (from different samples of the population) will include the true population mean.

A.1.5 Calculation of confidence interval

Confidence interval can be calculated using the following formula:

$$\hat{x} - \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2} \leq \mu \leq \hat{x} + \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2} \quad (\text{A.1})$$

In this formula, μ is the mean of population and $\hat{x}$ is the sample mean. The formula for sample mean is as follows:

$$\hat{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (\text{A.2})$$

In this formula, $x_1, x_2, \dots, x_n$ are independent identically distributed values of some performance measure of a system (in n independent runs of a model).

In equation A.1, $\hat{S}$ is a standard deviation. The formula for standard deviation is as follows:

$$\hat{S} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \hat{x})^2} \quad (\text{A.3})$$

In equation A.1, $t_{n-1, \alpha/2}$ denotes the upper $\alpha/2$ percentage point of the t distribution, which is used in unknown variance cases, with $n-1$ degrees of freedom. t is the tabulated value from Students t Distribution [116].

The lower confidence limit of the interval is:

$$\hat{x} - \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2} \quad (\text{A.4})$$

The upper confidence limit of the interval is:

$$\hat{x} + \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2} \quad (\text{A.5})$$

A.2 Accuracy estimation of the simulation results

All of the obtained results are in the 95% confidence interval level. Simulations were run 20 times for different arrival rates.

Table A.1: Results of confidence interval calculations of FSS for CDP with 1 call/second arrival rate.

Run number	Lower bound	CDP	Upper bound
	$\hat{x} - \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2}$	x_i	$\hat{x} + \frac{\hat{S}}{\sqrt{n}} t_{n-1, \alpha/2}$
1	0.45010	0.450120	0.45013
2	0.45010	0.450121	0.45013
3	0.45010	0.450119	0.45013
4	0.45010	0.450122	0.45013
5	0.45010	0.450120	0.45013
6	0.45010	0.450123	0.45013
7	0.45010	0.450117	0.45013
8	0.45010	0.450124	0.45013
9	0.45010	0.450116	0.45013
10	0.45010	0.450120	0.45013
11	0.45010	0.450117	0.45013
12	0.45010	0.450121	0.45013
13	0.45010	0.450122	0.45013
14	0.45010	0.450120	0.45013
15	0.45010	0.450130	0.45013
16	0.45010	0.450020	0.45013
17	0.45010	0.450127	0.45013
18	0.45010	0.450100	0.45013
19	0.45010	0.450120	0.45013
20	0.45010	0.450118	0.45013
Mean		0.450115	

As it can be seen from Table A.1, the obtained results for call dropping probability for arrival rate 1 call/second for FSS through the simulation are between upper and lower bounds of the interval with 95% confidence. Same tests were performed for all the simulated schemes.

APPENDIX B: Verification of the Obtained Results

B.1 Fully Shared Scheme

In this scheme, the CBP equals the CDP, which is given by the Erlang B formula for the M/M/c/c queue [116].

$$CDP = CBP = \frac{\frac{(c\rho)^c}{c!}}{\sum_{i=1}^c \frac{(c\rho)^i}{i!}} \quad (B.1)$$

In this formula, c is the number of channels in each cell and ρ is the load, and it can be found using the following formula:

$$\rho = \frac{\lambda}{c\mu} \quad (B.2)$$

where, $1/\mu$ is the mean service rate of handoff and new calls and λ is the arrival rate of handoff and new calls.

Table B.1 shows results for CDP and CBP obtained by simulation and by analytical analysis. As it can be seen from the table, results obtained from simulation are very close to results obtained by analytical analysis with a margin of 1% error.

Table B.1: Verification of results obtained from simulation of FSS with $c = 2$, $1/\mu = 1$.

λ	CBP Analytic	CBP Simulation	CDP Analytic	CDP Simulation
0.5	0.076923	0.078397	0.076923	0.072919
1	0.2	0.205587	0.2	0.206749
1.5	0.310345	0.315388	0.310345	0.316345
2	0.4	0.389587	0.4	0.406093

Figure B.1 compares results obtained from simulations and results obtained as a result of analytical analysis for CBP for FSS.

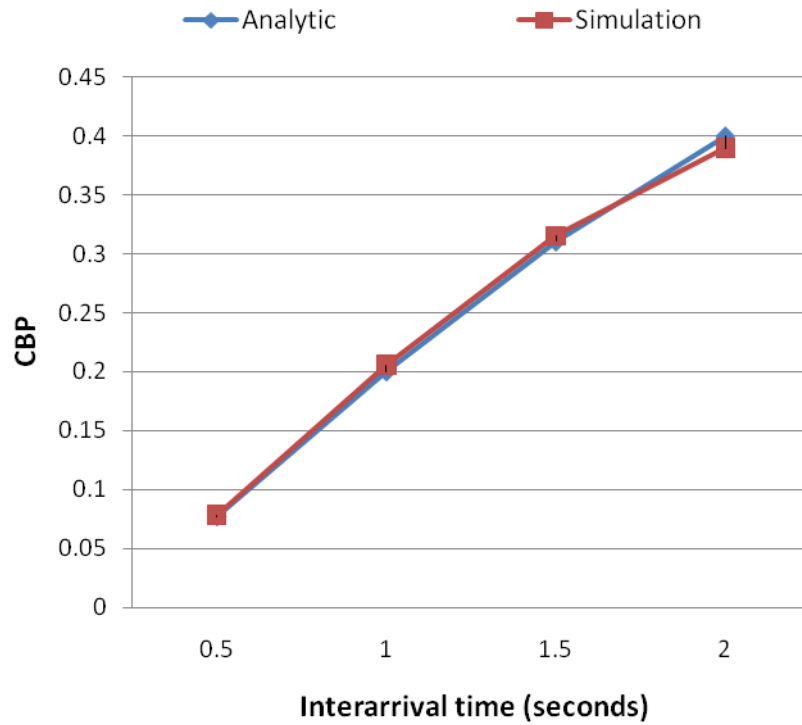


Figure B.1: CBP versus arrival rate for simulation and analytical results of FSS with $c = 2$, $1/\mu = 1$.

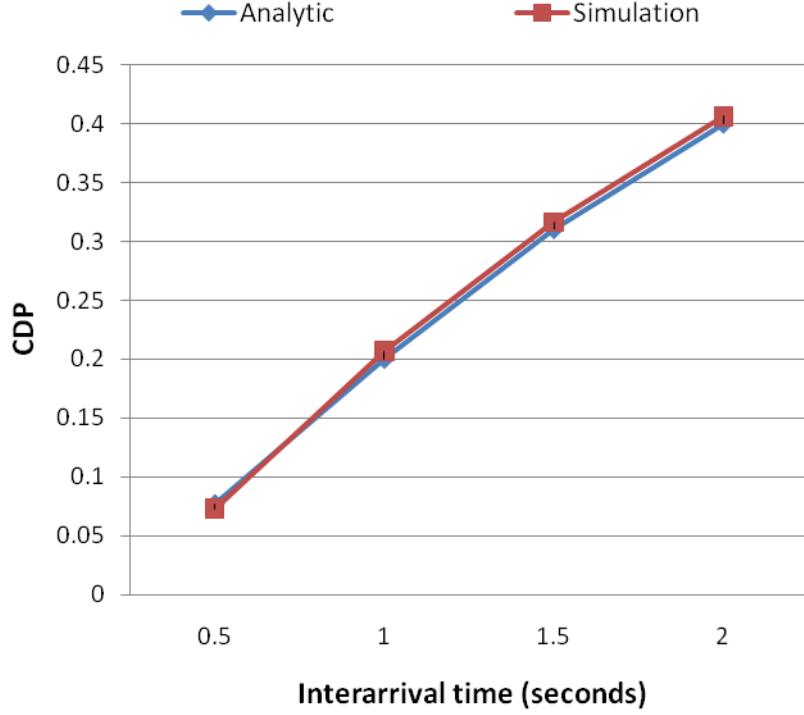


Figure B.2: CDP versus arrival rate for simulation and analytical results of FSS
with $c = 2$, $1/\mu = 1$.

Figure B.2 compares results obtained from simulations and results obtained as a result of analytical analysis for CDP for FSS.

B.2 Guard Chanel Scheme

The CDP and CBP of GCS can be obtained using the equations provided in [22].

The probability distribution P_0 is found as follows:

$$P_0 = \left[\sum_{k=0}^{C-C_h} \frac{(\lambda_h + \lambda_n)^k}{k! \mu_h^k} + \sum_{k=C-C_h+1}^C \frac{(\lambda_h + \lambda_n)^{C-C_h} (\lambda_h)^{k-(C-C_h)}}{k! \mu_h^k} \right]^{-1} \quad (\text{B.3})$$

where, $1/\mu_h$ is the mean service rate of handoffs, λ_h is the arrival rate of handoffs, λ_n is the arrival rate of new calls, C is the total number of channels, C_h is the number of channels reserved for handoffs.

The probability distribution P_j is found as follows:

$$P_j = \frac{(\lambda_h + \lambda_n)^j}{j! \mu_h^j} P_0 \text{ for } j = 1, 2, \dots, C - C_h \quad (\text{B.4})$$

$$P_j = \frac{(\lambda_h + \lambda_n)^{C-C_h} (\lambda_h)^{j-(C-C_h)}}{j! \mu_h^j} P_0 \text{ for } j = C - C_h + 1, \dots, C \quad (\text{B.5})$$

The CBP is found as follows:

$$CBP = \sum_{j=C-C_h}^C P_j \quad (\text{B.6})$$

The CDP is found as follows:

$$CDP = P_C \quad (\text{B.7})$$

Table B.2 shows results for CDP and CBP obtained by simulation and by analytical analysis. As it can be seen from the table, results obtained from simulation are very close to results obtained by analytical analysis with a margin of 1% error.

Table B.2: Verification of results obtained from simulation of GSC with $C = 2$, $C_h = 1$,

$$I/\mu = 1, \lambda_h = \lambda_n = 0.5\lambda.$$

λ	CBP Analytic	CBP Simulation	CDP Analytic	CDP Simulation
0.5	0.36	0.363051	0.04	0.039547
1	0.555556	0.556452	0.111111	0.111834
1.5	0.673469	0.667331	0.183673	0.18
2	0.75	0.738784	0.25	0.246441

Figure B.3 compares results obtained from simulations and results obtained as a result of analytical analysis for CBP for GCS.

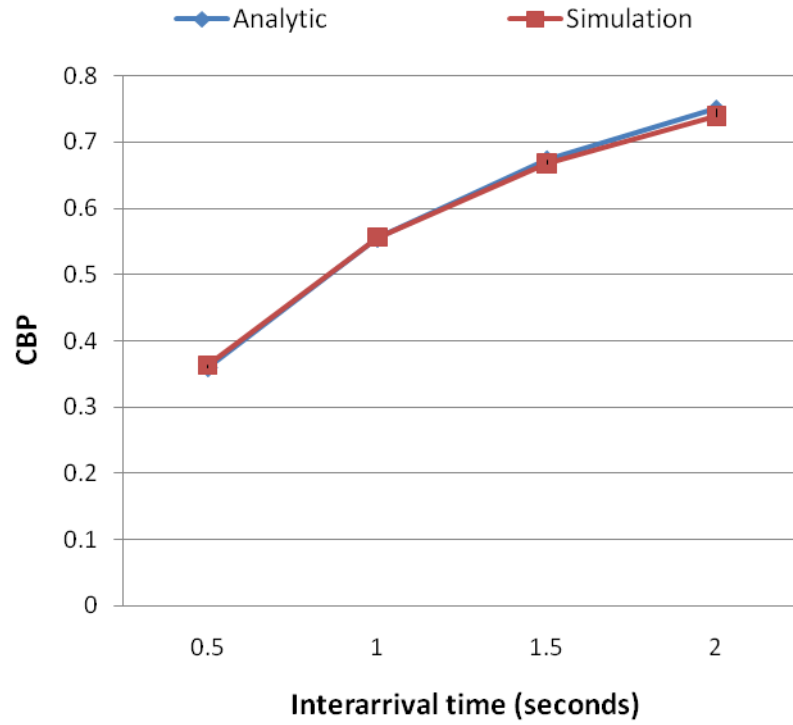


Figure B.3: CBP versus arrival rate for simulation and analytical results of GCS

with $C = 2$, $C_h = 1$, $I/\mu = 1$, $\lambda_h = \lambda_n = 0.5\lambda$.

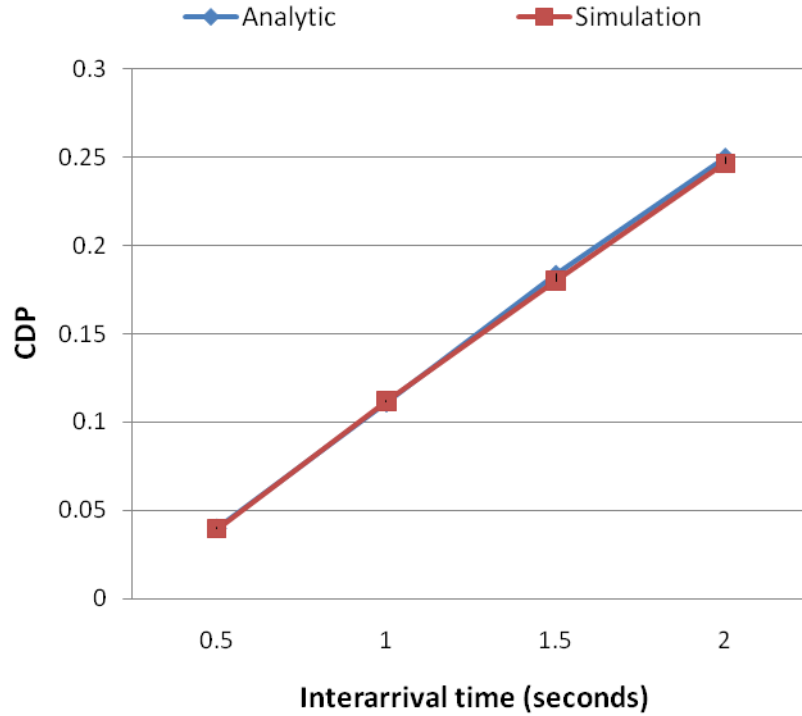


Figure B.3: CDP versus arrival rate for simulation and analytical results of GCS with $C = 2$, $C_h = 1$, $I/\mu = 1$, $\lambda_h = \lambda_n = 0.5\lambda$.

Figure B.4 compares results obtained from simulations and results obtained as a result of analytical analysis for CDP for GCS.

B.3 Conclusion

Simulation models of FSS and GCS were utilized as the main sources for all other simulation models, meaning that the rest of the schemes simulated during the course of this study were variations of FSS and GCS. As the results obtained from simulations of FSS and GCS were verified to be within 1% error ratio to analytical results, the rest of the simulations would show similar accuracy in results and can be considered reliable.