Congestion Control based on Dynamic Pricing Scheme and Service Class-based Joint Call Admission Control in Heterogeneous Wireless Networks

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As the candidate's supervisor, I have approved this dissertation for submission.

Signature Date

Dr. Aderemi Oluyinka Adewumi

Declaration

I declare that the contents of this dissertation are original except where due reference has been made. It has not been submitted prior to this time for any degree to any other institution.

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Dedication

This research thesis is dedicated to:

To my lovely parents, Arthur and Petronelle Mafuta

All the words in the world cannot express the immense love I have for you, nor the deep gratitude that I have for all the efforts and sacrifices that you have made as regards my health, education and general well-being. It is because of your support that I decided to embark on this noble research study and you have been there for me all through the study. I am thus expressing my eternal gratitude and infinite love by dedicating this research study first and foremost to you.

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Contents

List of Abbreviations

1G First Generation

2G Second Generation

3G Third Generation

4G Fourth Generation

3D Three Dimension

ACK Acknowledgement

AHP Analytical Hierarchical Process

AMPS Advanced Mobile Phone Services

bbu basic bandwidth unit

BSC Base Station Controller

BTS Base Transceiver Station

CAC Call Admission Control

CDMA Code Division Multiple Access

CDR Call Details Records

CRRM Common Radio Resource Management

DEA	Data Envelopment Analysis
DMM	Decision-Making Method
DP1	Dynamic Pricing 1
DP2	Dynamic Pricing 2
EDGE	Enhanced Data for GSM Evolution
GGSN	Gateway GPRS Support Node
GSM	Global System for Mobility
GPRS	General Packet Radio Services
GTP	GPRS Tunnelling Protocols
HCAC	Horizontal Call Admission Control
HWNs	Heterogeneous Wireless Networks
IMT-2000	International Mobile Telecommunications-2000
JCAC	Joint Call Admission Control
MSS	Maximum Segment Size
NGWNs	Next Generation Wireless Networks
NMT	Nordic Mobile Telephone
PDC	Personal Digital Communication
QoS	Quality of Services
RATs	Radio Access Technologies
RNC	Radio Network Controller
RRM	Radio Resource Management

SAW Simple Additive Weighting

SCJCAC Service Class-based Joint Call Admission Control

SGSN Serving GPRS Support Node

TACs Total Access Communications

TCP Transmission Control Protocol

TDMA Time Division Multiple Access

TMN Telecommunicações Móveis Nacionais

TOPSIS Technique for Order Preference by Similarity to Ideal Solution

UMTS Universal Terrestrial Mobile System

VCAC Vertical Call Admission Control

WCDMA Wideband Common Radio Resource Management

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WMAN Wireless Metropolitan Area Networks

WPAN Wireless Personal Area Network

WWAN Wireless Wide Area Networks

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Abstract

Next Generation of Wireless Networks (NGWNs) are heterogeneous and consist of several Radio Access Technologies (RATs) that coexist in the same geographical area. This heterogeneity of wireless networks is supposed to support multiple mobile terminal calls coming simultaneously to the RATs. NGWNs have to handle the Quality of Services (QoS) of any incoming user calls and manage the inflow of calls into the RATs. Congestion problem arises wherever there are multiple incoming user calls; especially during peak hours of the day. Several attempts have been made, as extracted from literature, to control this problem. This research is also a study that seeks to proffer solutions to improve congestion control in Heterogeneous Wireless Networks (HWN). Recent techniques for solving the congestion control problem are the application of the dynamic pricing and the Joint Call Admission Control (JCAC) algorithm. Dynamic pricing proposes incentives to users by increasing or decreasing the price of calls to encourage users to make calls during the off peak period while discouraging users from making calls during the peak period in a day. The Service Class-based JCAC (SCJCAC) algorithm is a technique that admits calls into a suitable RAT, based on the classes of services in such a way that different RATs are optimized in order to support the different classes of services. These two methods are used together to reduce congestion in the HWN. In this research, two recent dynamic pricing for congestion control are investigated, these schemes are compared and furthermore, a SCJCAC algorithm is proposed and modelled by using the multi-dimensional Markov process model for controlling congestion during the peak hours of the day in the HWNs. The simulation evaluates the performance of the proposed SCJCAC algorithm, while the two dynamic pricing schemes are also compared to the flat-pricing scheme during the peak hours.

Chapter 1

Introduction

1.1 Background concepts

A mobile network is composed of cells. Each cell has a local radio transmitter and receiver with enough power to enable connectivity with mobile terminals as illustrated in Figure 1.1. The set of cells form the Radio Access Technologies (RATs). The mobile network allows an exchange of voice and data between a phone network or Internet and a mobile terminal.

Cell site can be defined as a site where antennas, radio transmitters and receivers are placed to create radio coverage in a particular area. The communication from the mobile terminal to cell site is referred to as uplink transmission and when the communication is from cell site to the mobile terminal, it is known as downlink transmission. In a mobile network, there are mobile subscribers who make or receive calls while on the move without any disruptions to their calls. The network maintains the call and subsequently it proceeds uninterrupted. The network does this by handing the call off between cells in the mobile user's path, the mobility of users is illustrated in Figure 1.2.

Considering the explosive growth of mobile technology, mobile networks have several RATs in the same geographical area and several mobile users demand multiple services from the network

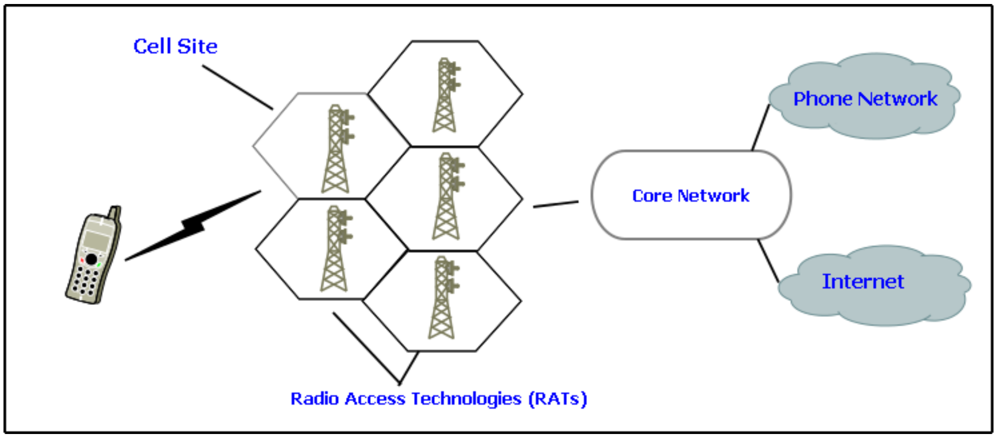

Figure 1.1: Mobile network [2]

as they are on the move each time, so a case of congestion is not always avoidable. Nyato and Hossain [1] specify that some media have video that are very sensitive to delays and require higher bandwidths. This requirement has led to the fast growth of mobile networks from the First Generation (1G) which offered only voice services with a bandwidth of 2.4 kbps - 9.6 kbps to the Fourth Generation (4G) which offers a range of services such as 3 Dimension (3D) applications, video, Mobile TV and fast Ethernet connections with bandwidths of up to 1 Gbps.

1.2 Generations of mobile network

1.2.1 First generation

In the 1980s, 1G of mobile cellular network became available. 1G used analogue transmission for voice service and it was able to support only voice services. The analogue transmission used by the 1G was dependent on the Frequency Division Multiple Process (FDMA), a radio system which requires that each user channel has a dedicated carrier band.

The 1G of mobile cellular network is a circuit-switch which means that the connection is established only when a person makes a call and the connection is maintained until he hangs up.

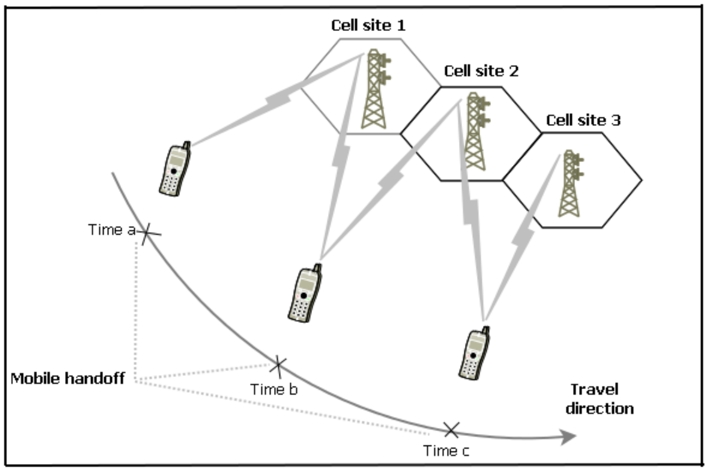

Figure 1.2: Subscribers mobility [2]

There exists several access technologies developed for the 1G of which the principals are:

- Advanced Mobile Phone Services (AMPS): This is an American cellular network that uses a frequency range between 800 and 900 Megahertz, it was also used in other countries.

- Total Access Communications (TACs): This is an European version of AMPS.

- Nordic Mobile Telephone (NMT): This is a Nordic version of the AMPS used in Norway, Finland and Sweden.

This generation of mobile networks was not secure, this means that anyone was able to intercept the call using a handle frequency scanner.

1.2.2 Second generation

The Second Generation (2G) mobile network was introduced towards the end of the 1980s [3]. The 2G system uses digital multiple access technologies known as Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA), which allowed the 2G give better data services, higher spectrum efficiency and more advanced roaming. Such that the number of cellular users grew and the need to increase network capacity became prominent and certain inventions were required. Pashtan [2] certified that the 2G supports basic data services with limited capacity since a single voice channel is used for the data transmission.

The 2G performed better than the 1G, as a result of the transition from analogue transmission to digital transmission. This transition provided the 2G, not only an improvement in voice quality but also the ability to store, to encrypt, to copy and to compress data. In addition, this transition offered the possibility of Internet access with increased speeds of 14.4kbps (theoretical), 9.6kbps - 19.2kbps (real).

Like 1G, 2G is also a circuit-switch. Access technologies were developed in 2G such as:

- Global System for Mobility (GSM)
- CDMA
- Personal Digital Communication (PDC)
- General Packet Radio Services (GPRS)
- Enhanced Data for GSM Evolution (EDGE)

1.2.3 Third generation

The Third Generation (3G) of mobile network perform all the functionalities of 2G, with added multimedia features which allow video telephony, audio and graphics applications. It was developed to have a higher capacity, faster data rates and better quality of service. The standard developed in 3G was IMT-2000 known in Europe as the Universal Terrestrial Mobile System (UMTS) and the air-interface technology for UMTS is Wideband CDMA (WCDMA).

Actually, network operators, through 3G, are able to offer users an enlarged range of advanced services while maintaining a greater network capacity through better spectral efficiency.

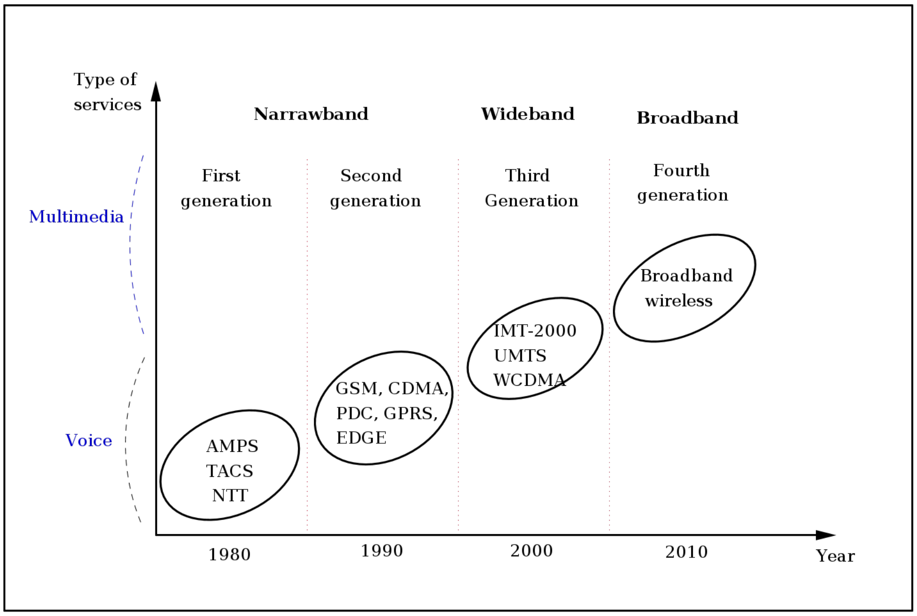

Figure 1.3: An overview of the evolution of mobile network [3]

1.2.4 Fourth generation

The emergence of new technologies in mobile network and the increasing demand of users have pushed researchers to create the 4G of mobile network systems. As observed by Kumar *et al.* [3], the 4G tries to accomplish new level of experience and also multi-service capacity which means an integration of different generations of mobile technologies existence such as GSM, GPRS, IMT-2000, WiFi, Bluetooth, etc.

The 4G has a common platform with all the prior developed technologies. The functionalities of the Radio Network Controller (RNC) and the Base Station Controller (BSC) are distributed to Base Transceiver Station (BTS) and to a set of gateways and servers. This makes the 4G less expensive but with faster data transfer. Figure 1.3 illustrates an overview of mobile network evolution.

1.2.5 Next Generation of Wireless Networks

The evolution of mobile networks have led to the invention of the Next Generation of Wireless Networks (NGWNs). The existing networks operate independently of each other based on the fact that they are homogeneous in nature. However, the NGWNs are expected to be heterogeneous in nature so that existing networks, called RATs, will be accessible within the same platform and radio resource allocation will be managed jointly [4].

Moreover, NGWNs are able to provide a high bandwidth access at time with good Quality of Services (QoS) [5]. Users would be more satisfied with the service quality of NGWNs as the probability of dropping or blocking calls will be reduced [6]. Since RATs will coexist together in the same area, the heterogeneous aspect of NGWNs will pose more challenges such as the mobility of users from one cell of RAT to another cell of a different RAT, the Radio Resource Management (RRM) of each RAT, the security aspect and many other areas. These challenges are presented in section 2.1.2 of this research study. Therefore, NGWNs present many interesting but challenging problems for researchers, hence the need for this study in a bid to address some of these challenges.

1.2.6 Joint Call Admission Control for Radio Resource Management in NGWNs

The technique for managing the RRM for the homogeneous wireless networks is called the Call Admission Control (CAC). CAC is a RAT technique aimed at determining whether a call request can be accepted or rejected into a RAT based on the availability of bandwidth in the network. However, this is handled differently for the NGWNs as the existing networks are operated independent of each others [7].

Moreover, NGWNs have applied an interoperability between RATs. There is an heterogeneous environment of wireless networks, which demand a joint management of radio resources of RATs known as the Common Radio Resource Management (CRRM). CRRM allows Heterogeneous

Wireless Networks (HWN) to achieve an efficient utilization of radio resources [8].

Hence, the Joint Call Admission Control (JCAC) is adopted to address the part of QoS provisioning and the RRM challenges in NGWNs, it deals with admission control requirements in NGWNs [9]. JCAC is a technique that ensures the allocation of radio resources and the provisioning of QoS requirements to users [10]. JCAC has to manage not only whether the call request is accepted or not like, the CAC but, in which appropriate or suitable RAT the call request would be accommodated. This fact is one of the advantages of the JCAC such that radio resources for each RATs are efficiently managed in order to reduce the probability of blocking or dropping calls. There exists diverse approaches of the JCAC to ensure an efficient admission of calls in NGWNs, these approaches would be discussed in the literature review section in this research study.

1.3 Problem statement

In the new millennium, mobile technology developments are on the increase leading to several problems such as the congestion problem, the deterioration of QoS, packet loss, etc. However, mobile communications can still be access by several people in motion and at the same time. The rising demand for mobile communication services necessitates the efficient use of the limited bandwidth and frequency spectrum.

The congestion problem is one of the problems faced with the use of wireless networks. The evolution of wireless networks which has led to NGWNs, as described above, allowed multiple RATs to coexist in the same geographical location supporting multiple services such as voice, video, data, etc. which makes the congestion problem more complex and intertwined.

This growth of mobile technologies involves an increasing utilisation of mobile technology services by users. Every day, mobile users request for a class of mobile services such as voice, video, data, multimedia messages, mobile internet, etc. and they expect to receive an efficient

QoS and the service providers also expect to receive good revenue. A congestion problem can occur at a certain time in the day, when increased request for the network services are common. The fact that NGWNs allow the coexistence of RATs in the same geographic area, imply an interoperability between them such that users are able to move from one cell to another and their call requests must not be disconnected or interrupted in order to maintain the QoS. This leads to the concept of radio resource allocation that occurs in HWNs. The system has to accommodate the new calls and handoff calls into an appropriate RATs palliate to resolve the problem of blocking calls or dropping calls. The calls can be accommodated into a suitable RATs according to the type of services such that some classes of services can be accommodated in a specific RAT, this approach is called Service Class-based JCAC (SCJCAC) algorithm, where the scheme has to control the admission of the classes of services into a suitable RATs to accommodate the type of services requested. The following research questions are examined in this study:

- How can the probability of congestion during the peak hours of the day be reduced into HWNs?

- How can calls be accommodated into the appropriate RAT in order to manage the radio resource allocation of the RATs in HWNs?

1.4 Research objectives

Several researches have been done to find the scheme that could help provide solutions to the problem of congestion in networks, to increase the efficiency, network capacity and to make user demand fit the limited capacity available, such that multiple RATs can coexist in the same geographical area (dynamic pricing approach, multipath routing approach [11]).

The main objectives of this research are to:

1. investigate two different dynamic pricing approaches to reduce the congestion problem in the HWNs during the peak hours of the day;

2. propose the flexible SCJCAC algorithm modelled with the Markov decision process which is further integrated with one of the dynamic pricing approaches for an efficient accommodation of varying classes of services into a suitable RAT.

Furthermore, the secondary objectives of this research study are to:

- compare the system's performance under the two dynamic pricing schemes and the flat pricing scheme, and how these link into a HWN;
- determine the new call blocking and handoff call dropping probabilities into a HWN for an increasing arrival rate of calls more especially during the congestion period; and
- manage the call admission procedure of real-time (voice) and non-real-time (data) into different RATs, which are the GPRS and the UMTS, by using the flexible SCJCAC algorithm.

1.5 Research methodology

This research thesis uses the dynamic pricing approach to reduce congestion in wireless networks by charging a higher price to users during the peak hour period so that users are sensitive to price. Dynamic pricing gives incentives to users usually aimed at encouraging or discouraging them by decreasing or increasing the price. CAC, when integrated with dynamic pricing is expected to give the best result for solving congestion in homogeneous wireless networks. Many researches have developed pricing schemes in wireless network with respect to this integration between CAC and the dynamic pricing scheme by using different methods.

The JCAC has been developed for HWNs such that CAC in homogeneous wireless networks is only responsible for deciding whether or not a user may be admitted into the network. The SCJCAC algorithm approach is used to distribute classes of services into the suitable RATs. Two classes of services and two RATs are considered to further illustrate this approach. Calls will be accommodated in the RATs based on the types of services such that a service request is handled by the most suitable RAT.

The numerical approach is used to simulate the dynamic pricing approaches and the SCJ-CAC algorithm in a HWNs using PYTHON language. The multi-dimensional Markov decision process is the model used for the numerical approach which is also used for the modelling of SCJCAC algorithm in the HWNs. The performance metric of the system is evaluated for the new call blocking and handoff call dropping probabilities and the users' utility to see the level of user satisfaction.

1.6 Scopes and limitations

This research study considers wireless networks, precisely, the HWN. This particular study is limited to two classes of services namely voice and data and two RATs namely GPRS and UMTS. The research is based on the congestion problem that occurs in HWNs during business hours revealing the need for this problem to be reduced or controlled. The RATs considered in this research are assumed to be fully overlapped; where all RATs in HWNs offer a full coverage. Two approaches are used to control congestion in HWNs. The first approach is the dynamic pricing approach which gives incentives to users to make calls in order to encourage or discourage them by increasing or decreasing the price during the business hours. The second approach is the JCAC algorithm which allows the admission of calls into the networks and decides whether or not the calls could be accommodated into an appropriate RAT. The JCAC algorithm considered in this research study as a means of resolving the congestion problem is a flexible SCJCAC algorithm.

The data set used for simulation is limited and is based on a common evaluation of traffic intensity during business hours, this is only real and practical data are not easily accessible. Two dynamic pricing schemes are investigated. However, only one dynamic pricing is integrated with the proposed flexible SCJCAC algorithm.

1.7 Contribution to knowledge

The major contribution of this research is that it investigates two previous dynamic pricing schemes and a proposed SCJCAC algorithm in a bid to proffer a solution that would reduce congestion during the peak hours of the day in HWNs. The JCAC algorithm chosen is a flexible SCJCAC algorithm modelled with the Markov decision process.

1.8 Outline

The rest of this thesis is structured as follows:
Chapter 2 presents a background and literature review of some important concepts of mobile networks such as the HWNs, the CRRM, the JCAC algorithm, the network congestion problem, the pricing schemes in NGWNs and some related researches on the integration of the dynamic pricing scheme with the CAC algorithm are also reviewed.

Chapter 3 presents an analytical model for a flexible SCJCAC algorithm by using the Markov decision process, a model of blocking and dropping probabilities and a discussion on two recent dynamic pricing schemes.

Chapter 4 presents the simulation results and the discussion of the general results obtained for the two dynamic pricing schemes and for blocking and dropping probabilities for the cases where congestion occurs during the peak hours and when the arrival rate increase. The users' utility of the classes of services are also evaluated.

Chapter 5 contains the conclusion and recommendation for future research.

Chapter 2

Background information and literature review

This chapter discusses some background information on the NGWNs, the CRRM, the JCAC algorithm, the network congestion, the pricing schemes and presents a review of the literature on dynamic pricing and the JCAC algorithm. Some related researches on the integration of dynamic pricing and CAC are investigated and the recent JCAC algorithm technique is discussed.

2.1 Next Generation of Wireless Networks

NGWNs involve the coexistence of all previous generations in the same area and multiple RATs such as GSM, UMTS, WiMAX, etc., in the same platform. This implies that the architecture of NGWNs which is the 4G, will constitute these different RATs, and it will provide the capability to support a wide range of services [6] such that the user demand is increasing which lead to the increase in the use of high bandwidth consuming services.

2.1.1 Heterogeneous Wireless Networks

HWNs can be defined as computer networks connecting several systems using different types of RATs. In addition, HWNs allow different technologies to be made available to users within the same coverage and different wireless access networks to operate with different service providers. HWNs are linked to the NGWNs where multiple RATs are integrated, and are characterized by the fact that they can support different users and applications that have different QoS requirements [5].

A wireless network is defined as a computer network that is not connected by cables but rather by radio waves. Through the wireless network, a user has the ability to stay connected while moving around a geographic area which is more or less extensive, leading to the issue of mobility. Mobility is one of the challenges of HWNs because the mobile subscriber has to be connected to the network from any location. HWN has implemented the vertical handover process in addition to the existing horizontal handover process in the homogeneous wireless networks as 2G in order to ensure that mobility is made possible.

When a mobile subscriber moves away from its located cell to another cell, its mobile terminals will be connected or allocated to the base station of the cell of his next location without the user experiencing a connection failure. This is known as the horizontal handover as long as the base station to which the connection has been transferred belongs to the same RAT with the preceding base station. The vertical handover process is described as a case where the base station to which the connection is transferred does not belong to the same RAT [1].
Figure 2.1 illustrates the horizontal handover and vertical handover processes. Wireless networks are based on connections made using radio-waves (radio and infra-red) instead of the usual cables. There are several technologies which are distinguished in part by the transmission frequency used, the throughput and the transmission range. Moreover, the installation of such networks does not require the existence of the infrastructural heavy facilities as is the case with wired networks which produced a rapid development of this type of technologies. There exists several types of wireless networks, they are the:

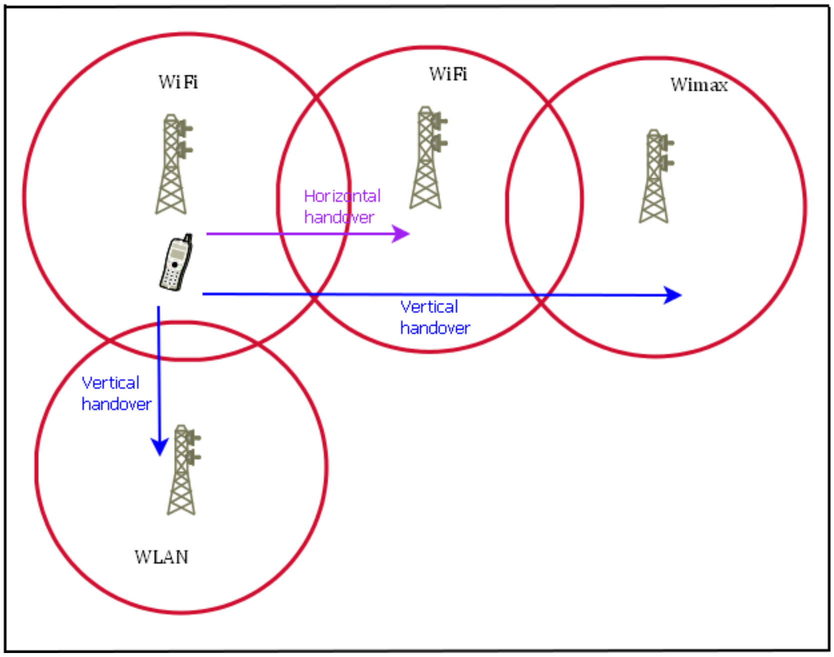

Figure 2.1: Horizontal and vertical handover

- Wireless Personal Area Network (WPAN): WPAN interconnects devices centred around an individual person's workspace.

- Wireless Local Area Network (WLAN): WLAN covers an equivalent of a hundred meters, it allows for connection to be made between the terminals present in the coverage area.

- Wireless Mesh networks: These are communication networks made up of radio nodes organized in a mesh topology.

- Wireless Metropolitan Area Networks (WMAN): WMAN are a particular type of wireless network that connect several WLANs.

- Wireless Wide Area Networks (WWAN): WWAN are wireless networks that cover large areas e.g. neighbouring towns and cities or countries.

Two categories of wireless network are homogeneous wireless networks, where a single wireless technology is available to users and HWN, where several wireless technologies coexist together and are accessible to users. With the evolution and the emergence of new technologies for wireless networks, the homogeneous wireless network no longer has a place in the market for wireless networks, since the RATs (wireless technologies) need to be in constant communication and because there has to be interoperability between them. HWN is the wireless technology that allows for the communication and the coexistence between RATs and users with a multi-interface terminal, so that there would be network access to different services providers using various technologies [12].

2.1.2 NGWNs challenges

There exists several challenges with the use of NGWNs, these have to be designed and implemented [13], [14], [15]. These challenges can be identified in the following aspects:

2.1.2.1 Interworking

As specified above, the NGWNs will group different RATs in the same area, which implies the existence of interworking between them such that users will have the possibility of being connected to any RATs available in a platform. Thus, NGWNs have a challenge to develop interworking techniques for the different RATs which operate independently of each other.

2.1.2.2 QoS provisioning

NGWNs have a QoS provisioning challenge. The fact that NGWNs will support several services with different QoS requirements and different user QoS requirements, means NGWNs have to provide an optimal QoS. In addition, the lack of mobility management and location management for efficient access and for timely service delivery are also problems that NGWNs have to manage [16], [9].

2.1.2.3 Mobility management

NGWNs have mobility issues, as users would most times be on the move, the management of this can pose a serious challenge. The location and handoff managements in NGWNs have to be accomplished in a seamless fashion among different RATs. The horizontal handoff, vertical handoff and roaming services have to be considered and supported in NGWNs, while the QoS requirement has to be maintained.

2.1.2.4 Radio Resource Management

RRM when not properly operated poses a challenge for NGWNs because the good management of RRM can help to avoid congestion problems. A CRRM algorithm needs to be developed such that NGWNs can handle the radio resources from different RATs jointly [17], [18].

2.2 Radio Resource Management in NGWNs

The RRM plays an important role in NGWNs as it has to ensure the desired Quality of Services (QoS) to users. This means that it has to maintain this quality in the required level in wireless networks. The efficient RRM is very essential in wireless networks because the NGWNs environment groups several RATs with different applications, this shows the diversified nature of QoS requirement from the wireless networks [13].

2.2.1 RRM techniques

RRM algorithms comprise techniques described by Ahtiainen *et al.* [19], Liu and Chao [20] and Goodman *et al.* [21], which are presented as follow:

2.2.1.1 Handover control

Handover control has to guarantee connectivity for users even when they move around. The handover function maintains the traffic connection for users on the move from one coverage area to another by establishing new connections in the new coverage area and then releasing the old connection.

2.2.1.2 Power control

The power control consists of adjustments of the power to the desired QoS such that when the power is increasing, the network capacity also increases and interference which leads to the degradation of the QoS is also increased. Thus an effective power control ensures that the capacity of the network is maximized and the interference is minimized [21].

2.2.1.3 Call Admission Control

The CAC decides whether a new call is admitted into the network by checking the network's resources such that the QoS of existing connections is not compromised. An efficient CAC algorithms for NGWNs should predict the load of the network if a new call is admitted [19].

2.2.1.4 Scheduling

The scheduling algorithms are required to prioritize users' traffic in order to meet different requirement of the QoS while fully utilising network resources [20].

2.3 Common Radio Resource Management

CRRM is a technique designed to manage, in a joint way, the radio resources from different RATs such that HWNs are envisaged as joint cooperative management of different technologies in which the service providers have to satisfy the users need or service demands in an efficient way by exploiting the properties of HWNs [8]. The CRRM technique is also able to facilitate the management of vertical handover and is able to optimize the utilisation of resource in the terms of QoS requirements, network load, cost, etc. [22]

2.3.1 Functional model of CRRM

The functional model for the CRRM consists of two functional entities which are the:

- RRM entity: This is an entity responsible for the RRM of one resource pool, the resource pool is characterized by having its own RRM functionality.

- CRRM entity: This is an entity responsible for the coordination of neighbouring RRMs.

As illustrated in Figure 2.2, the CRRM entity interacts with the RRM entity in NGWNs, this interaction is characterized by two basic functions which are:

- The information reporting function: This function allows RRM entities report relevant information to their controlling CRRM entity. The exchanged and reported information include the cell information such as capabilities and capacities, average buffer delay, etc and the dynamic measurement information such as cell load, transmitted power level, etc. The RRM report can be done either periodically or can be event triggered [23]. Information reporting or exchange information is possible between CRRM entities in order to know the status of corresponding RRM entities [24].

- The RRM decision support function is a function in which the RRM has to describe the way in which CRRM and RRM entities should interact with each other in making decisions [23].

Wu and Sandrasegaran [23] specified that there are two different RRM decision-making methods (DMM) in the RRM decision support function, namely the CRRM centred DMM and the local RRM centred DMM. The CRRM centred DMM works in such way that the CRRM entity makes the decisions and then informs the RRM entities to execute them. The local RRM centred DMM works such as the CRRM entity has to advise the RRM entities [23]. However, the final decision is made by the local RRM entities rather than the CRRM entity [23].

2.3.2 CRRM functionalities

The CRRM has been designed to manage in efficient ways the resource pools over an heterogeneous network environment, which explains the construction of its functionalities [24]. It is worth mentioning that, when the RRM functionalities such as admission control, congestion

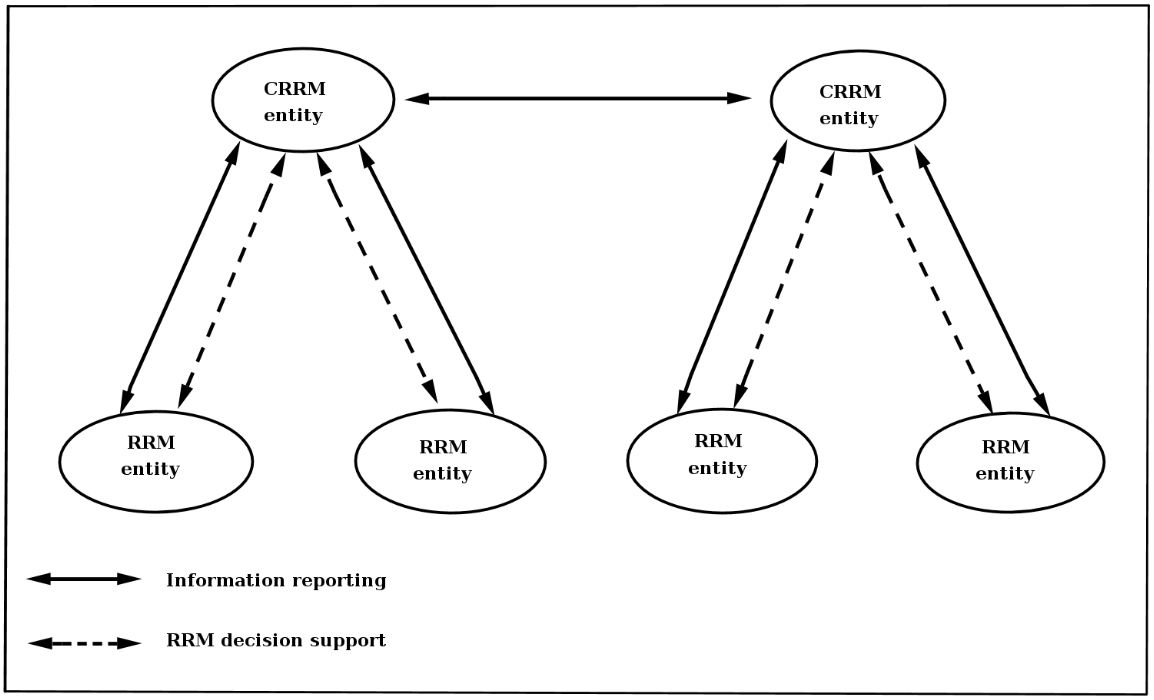

Figure 2.2: CRRM functional Model [23], [24]

control etc. are coordinated between the different RATs in an heterogeneous environment, they explicitly become common e.g. the common admission control and the common congestion control [24]. Different possibilities or approaches are envisaged to incorporate the CRRM functionalities into the RRM functionalities in order to support the different procedures.

2.3.2.1 No CRRM functionalities

In this specific case, different RATs are operated in an heterogeneous environment, there is no coordination carried out between them, this implies that no specific functionalities are associated with the CRRM level [24]. The decisions in the RRM entity are taken without any extracted or prior knowledge from the existing radio network conditions in other RATs.

2.3.2.2 Initial RAT Selection and Vertical Handover

This case allows an association based on the initial RAT selection and vertical handover algorithms with the CRRM entity. The local RRM entities provide RRM measurements where cell load measurements and the list of candidate cells for the different RATs are included, this allows the CRRM know the availability of each RAT.

2.3.2.3 Common admission and congestion control

When the operations between CRRM and RRM entities are considered, the other possibility envisaged is to move those functionalities operating on a long-term basis, such as the admission and congestion control algorithms, into the CRRM entity while keeping the functions that operate at the radio frame level, such as packet scheduling or the power control, in the RRM entity such that they require frequent information exchange between the CRRM and the RRM entities [24].

2.3.2.4 Common packet scheduling

In the CRRM entity, the execution of joint scheduling algorithms is the higher degree of interaction existing between local RRM and CRRM [24], [25]. It is specified that this approach can be realised with frequent RAT switching for a given terminal or with simultaneous links with different RATs [24].

2.3.3 Investigations in CRRM

Investigations have been done to unravel CRRM strategies for NGWNs:

Vulic *et al.* [22] propose an integration between WLAN-UMTS at the radio access level. This interworking approach that incorporates WLAN into UMTS and RAT, provides an additional licence-free capacity to operators with better performance of a good vertical handover.

Hasib and Fapojuwo [26] proposed an adaptive CRRM scheme to jointly utilize the resource in the different RATs while maintaining the desired QoS, the scheme minimizes the rate of unnecessary vertical handoffs and then provides stable communication without degrading the call blocking probabilities.

Yang *et al.* [27] proposed a traffic split scheme in order to minimize the throughput based on CRRM for two oriented access networks. After simulation, the proposed scheme has improved the throughput and reduced the delay of the networks.

Shi *et al.* [28] proposed a CRRM algorithm for NGWNs based on load balance and service characteristics, where the algorithms have to select an available access and handoff network for all the new and handoff calls respectively, according to the network load or service type etc. The results of this scheme have shown that it is able to reduce the call blocking probability and improve the throughput of HWNs.

2.4 JCAC algorithms

2.4.1 Benefits for JCAC algorithms

2.4.1.1 Efficient radio resource utilisation

The JCAC algorithms have an objective to optimize the utilisation of radio resource in an efficient manner among the available RATs while providing the required QoS to the users [10].

2.4.1.2 Consistent QoS provisioning

Falowo and Chan [10] specified that a single RAT could not always satisfy the QoS requirements of all subscribers as a result of its limited capacity and coverage. These requirements are: the packet-level requirements quantified in terms of packet loss, jitters, delay data rate [10], [29]; whereas, Connection-level requirements quantified in terms of call blocking / dropping probability [30], [10]. If the packet-level requirements of an ongoing call cannot be met by a specific RAT, the JCAC algorithm will admit the call into another RAT which guarantees its QoS requirements [30]. Thus improving the packet level QoS requirement. In the case where new call is not admitted into a RAT or a handoff call to a target cell in its current RAT, due to radio resource unavailability, it will be admitted into another RAT [10]. Then, the new call blocking probability and handoff call dropping will be reduced, which means, connection-level QoS will be improved [10].

2.4.1.3 Overall network stability

The JCAC algorithms are used for the efficient distribution of network load among available RATs such that, if there is an independent CAC in each RAT, some RATs will be overloaded while the other RATs will be underutilized, thus handing over some ongoing calls from one RAT to another RAT [31]. The JCAC algorithm has to ensure overall network stability. As specified by Falowo and Chan [10], the major chbetweenallenge is to monitor the network state at periodic intervals of time in a way that the load in each access network can be measured and then the JCAC algorithm is notified.

2.4.1.4 Enhancement of users satisfaction

Users may have different preferences for different service when the JCAC algorithms are used. The users' preferences depends on different factors like service price, QoS, etc. The JCAC algorithms may consider the enhancement of user satisfaction by considering the users' preferences [10].

2.4.1.5 Increase in operator's revenue

The JCAC algorithm can be used to increase the operators' revenue by the efficient utilisation of radio resources in NGWNs [10].

2.4.2 Requirements for JCAC algorithms

It is necessary that JCAC algorithms meet certain requirements in order for them to perform effectively. As presented by Falowo and Chan [10], some of the requirements are summarized in the subsections below:

2.4.2.1 Multi-services

The JCAC algorithms must be able to support multiple services such that the NGWNs will have an increased capacity to sustain several services, for example voice, data, video, multimedia messages etc. Users have different service requirements and network operators expect increasing revenue, which means JCAC algorithms need to support multiple services in order to enhance user satisfaction and to increase operators' revenue respectively.

2.4.2.2 Efficiency

The JCAC algorithms are expected to be efficient in order to guarantee the QoS requirement and to achieve radio resource utilisation in NGWNs.

2.4.2.3 Simplicity

JCAC algorithms should be simple to permit low computational overhead and thus to prevent it from incurring additional delays in the network. However, a very simple JCAC algorithm may not be able to achieve a high radio resource utilisation. Therefore, there is a trade-off between simplicity and efficiency of the JCAC algorithms.

2.4.2.4 Scalability

The JCAC algorithms should be able to manage the increased network capacity and the size of individual RATs, such that, there is an increased demand for multimedia data service. Moreover, the JCAC algorithms should be able to minimize the amount of information exchange in HWNs as large amount of information may lead to significant overhead costs in NGWNs.

2.4.2.5 Stability

It is important that JCAC algorithms are able to ensure overall stability in NGWNs in order to avoid situations of instability where some RATs are overloaded whereas other RATs are underutilized. Therefore, JCAC algorithms must avoid such situations by being able to achieve load balancing among the available RATs.

2.4.2.6 High execution speed

The JCAC algorithms should have high execution speed to prevent additional delays in the network and to enable the admission control operate in real-time. A high execution speed of JCAC algorithms will enhance the QoS in NGWNs.

2.4.3 RAT selection approaches for JCAC algorithms

There are different approaches that can be utilised in selecting an appropriate RAT for an incoming call in HWNs that allows JCAC algorithms to be categorized. These RAT selection approaches are summarized as follows:

2.4.3.1 Random selection-based JCAC algorithms

The random selection-based JCAC algorithms comprise a random selection when new or handoff calls arrive, if there is not enough radio resource in the selected RAT, the call will be blocked or dropped. Certain variants of random selection-based JCAC algorithms are allowed to select an alternative RAT if the previously selected RAT does not have enough radio resource to accommodate the call, resulting in being the call blocked, if none of the randomly selected RATs can accommodate it. This approach is easy to implement. However, it has a high call blocking probability and less radio resource utilisation [10].

2.4.3.2 Load-based JCAC algorithms

The load-based JCAC algorithms consist of a uniform distribution of traffic load among all the available RATs in HWNs. Suleiman *et al.* [32] and Tolli and Hakalin [33] specified that balancing load among multiple RATs in HWNs allows for a better utilization of the radio resources. This approach ensures high network stability due to uniform load distribution, which is its major advantage. However, it is a network-centric, which may lead to low user satisfaction [10].

2.4.3.3 Service class-based JCAC algorithms

The SCJCAC algorithms allow for the accommodation of incoming calls into a specific RAT according to these classes of services: voice, data, video such that some RATs are more optimized to support certain classes of services [10], [34]. This approach ensures a high packet-level QoS which is one of its advantages. However, it may lead to a highly unbalanced network load. The SCJCAC algorithms can be classified into two different categories, which are the rigid and flexible categories. A rigid SCJCAC algorithm can admit an incoming call of a specific class of service into a specific RAT, if there is not enough radio resources in the preferred RAT, the call cannot be accommodated into another RAT, thus, the call will be blocked. A flexible SCJCAC algorithm, on the other hand, if there is not enough radio resources into the preferred RAT, another RAT can be selected to accommodate that call. A flexible SCJCAC algorithm gives a lower call blocking probability than a rigid SCJCAC algorithm.

Zhang [34] has investigated a SCJCAC algorithm in which GSM/UMTS was considered with an overlapping coverage. Three classes of services have been considered: voice, streaming and data, where GSM is the preferred RAT for voice calls and UMTS is the preferred RAT for streaming and data. Zhang [34] proposed different scenarios to evaluate the performance of the SCJCAC algorithm and has compared these different scenarios using simulation. Results show the performance of each proposed scenarios with their loss probabilities.

Song *et al.* [35] have investigated a SCJCAC algorithm for WLAN/UMTS with two classes of services: voice and data. They consider a case where there is double coverage, which works as follows: when the call is a voice call, the algorithm tries to admit the voice call in UMTS by priority, if there is no available bandwidth in the UMTS to accommodate the call, the algorithm will try to admit the call into WLAN, otherwise the voice call is blocked. When the call is a data call, the algorithm will try to admit the call into WLAN. If there is no available bandwidth in WLAN, the data call is blocked. Results show that the proposed SCJCAC algorithm reduces the average number of handoff per voice calls such that the main objective of their scheme is to reduce the frequency of handoff voice calls in the HWNs.

2.4.3.4 Path loss-based JCAC algorithms

The path loss-based JCAC algorithms admit a call into an appropriate RAT based on the path loss measurements taken in each RAT cells. They have the advantage of a low bit-error rate and high throughput. However, they cause a high frequency of the vertical handover [10], [36].

2.4.3.5 Service cost-based JCAC algorithms

The service cost-based JCAC algorithm is based on the fact that service cost differs from one RAT to another. Accordingly, this approach can admit the ongoing calls into the least expensive RAT, allowing subscribers to incur the least service cost in the HWNs. The overall service cost incurred by subscribers will be reduced. However, this approach leads to a highly unbalanced network load [10].

2.4.3.6 Network layer-based JCAC algorithms

The network layer based JCAC algorithms consist of admission calls into a specific layer in the case of overlaid networks. When the layer is not able to accommodate the call, the network layer-based JCAC algorithm tries to admit the call into the next available layer [10]. This approach has the advantage of being simple but it leads to a highly unbalanced network load.

2.4.3.7 Cost/utility function-based JCAC algorithms

The cost/utility function-based JCAC algorithms admit ongoing calls into an appropriate RAT according to some cost or utility function which is derived and based on a number of criteria. The cost/utility function-based JCAC algorithms are frequently complex and incur high computational overheads. However, they are very efficient [10].

2.4.3.8 Computational intelligence-based JCAC algorithms

The computational intelligence-based JCAC algorithms select the appropriate RAT for ongoing calls by applying some computational intelligence techniques such as the fuzzy logic, fuzzy neural or genetic algorithm to some RAT selection criteria. This approach has the advantages of being very efficient and being able to improve the users' satisfaction. However, it is very complicated to implement [10].

2.5 Network congestion

Network congestion occurs when the network is overloaded by so much data in the link or node leading to the deterioration of the QoS. The effects of congestion in the network leads to packet loss, blocking connection or queuing delay [37]. Gosh [37] specified that congestion in networks can easily be defined as the presence of higher rates of inputs to a router compared with the rates of outputs.

2.5.1 Congestion collapse

The congestion collapse is a situation where congestion is so high that the throughput drops to a low level, this implies low communication in the network. Moreover, Jain *et al.* [38] described congestion stating that "It can be a stable state with the same intrinsic load level that would by itself not produce congestion. This is because it is caused by the aggressive retransmission used by various network protocols to compensate for the packet loss that occurs as a result of

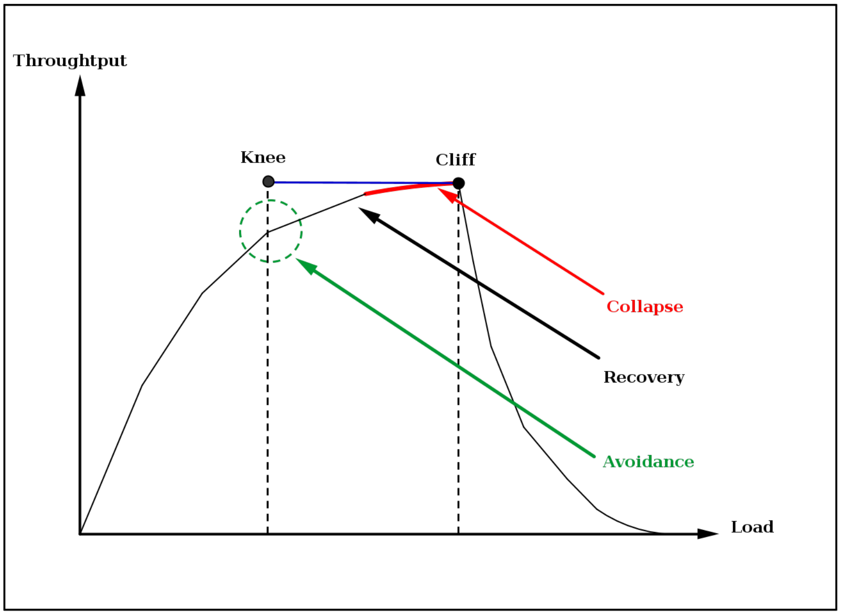

Figure 2.3: Illustration of congestion collapse

congestion, a retransmission that continues even after the load is reduced to a level that would not have induced congestion in itself". Congestion collapse is illustrated in Figure 2.3, where knee the is the point after which the throughput increases very slowly and the delay increases quickly, and cliff is the point after which the throughput starts to decrease very quickly till it reaches zero and the delay approaches infinity [37]. At the right side of cliff is the congestion collapse region.

2.5.2 Congestion avoidance

Congestion avoidance can be defined as a situation where congestion has to be avoided. Congestion avoidance allows a network to operate in the region of low delays and high throughput. It is a preventive mechanism against the congestion situation. Jain *et al.* [38] have declared that congestion avoidance ensures that mobile users are encouraged to increase their load as long as it does not affect their response time and when their load affects their response time, they are encouraged to decrease it.

Congestion avoidance aims to oscillate around the knee to avoid congestion without significant degradation in performance. Congestion avoidance thus aims to stay at the left-hand of knee to avoid congestion [37].

2.5.3 Congestion control

Congestion control intervenes when congestion occurs, it is thus a recovery mechanism. According to Gosh [37], congestion control has the following goals:

- Staying to the left of cliff to avoid congestion collapse, which is a catastrophic region.
- Guaranteeing the stability of operations or transmission of packets in networks to avoid congestion collapse.
- Keeping the networks functioning in an efficient way which means low delay, low loss, high throughput and high utilization.
- In the network, congestion control has to provide fair allocations of bandwidth among competing flows in a steady state.

As specified by Gosh [37], some of these goals are not always achievable due to the fact that there are distributed systems. Ahuja [39] specified that one of the easiest way of controlling congestion in wireless networks is to prevent new connections from starting up if congestion is already suspected. However, Jain *et al.* [38] proposed that this approach has a disadvantage, a feature of any reservation scheme, that reserved resources cannot be used and cannot be left idle even when other users have been denied permission.

2.5.4 Transmission Control Protocol congestion control

Most of the vital traffic in the network are actually carried on to the Transmission Control Protocol (TCP), this is why congestion control at the TCP level is very important.
TCP has a mechanism to control congestion and this is implemented at the sender level. The

sender has two parameters which are the congestion window (*cwnd*) and the slow start thresh-hold value (*ssthresh*). The initial value is the advertised window size at the *ssthresh* [37]. The TCP congestion control works in two different modes which are enumerated below:

- Slow start where $cwnd < ssthresh$

- Congestion avoidance where $cwnd >= ssthresh$

2.5.4.1 Slow start

Essentially, TCP is based on bytes and increments by the Maximum Segment Size (MSS) where the unit is the segment size. Gosh [37] specified that the slow start works via the following steps:

- Firstly, through the initial value which is the slow start, where the congestion window is equal to 1:
  - Set $cwnd = 1$

- Secondly, the receiver sends, for each packet, an Acknowledgement (ACK).

- Thirdly, for each time the sender receives an ACK, the congestion window is increased by 1 segment as follows:
  - $cwnd = cwnd + 1$
  - If an ACK acknowledges two segments, *cwnd* is still increased by only 1 segment.
  - Even if ACK acknowledges a segment that is smaller than MSS bytes longs, *cwnd* is still increased by 1

2.5.4.2 Congestion avoidance

The congestion avoidance works by following these steps [37]:

- Congestion avoidance starts only if *cwnd* has reached the slow start threshold value.

- If $cwnd$ becomes greater or equal to $ssthresh$, then, each time an ACK is received and an increment of $cwnd$ occurs as follows:

  – $cwnd = cwnd + 1/[cwnd]$
    where $[cwnd]$ is considered as the largest integer which is smaller than $cwnd$.

- $cwnd$ increases by one only in the case where all $cwnd$ segments have been acknowledged.

- Congestion is assumed in the networks when the TCP detects a packet loss.

- A TCP sender detects lost packets via receipt of duplicate ACK or timing out of the retransmission timer.

- TCP interprets a time-out as a binary congestion signal, when a time-out occurs, the sender performs the following:

  – $cwnd$ is reset to 1 while $ssthresh$ is set to half the current size of the congestion window and the slow start is entered.

2.6 Pricing approach in NGWNs

The pricing approach has been designed to offer profitable revenue to the service providers as well as allow a great QoS for the mobile users. It is also designed to manage the access of users to the network channels by charging a specific price to them with the goal of alleviating network congestion.

Gizalis and Vergados [40] have performed a survey of different pricing schemes based on their ability to adapt to the needs of service providers and their users during the entire service period.

2.6.1 Factors affecting price

There are various factors that affect the way price is determined by service providers for the users. These factors can be competition, demand for a specific service, cost of delivering a service and the cost of spectrum.

2.6.1.1 Competition

Competition in wireless networks is an important factor that affects the price level such that the wireless networks area has became a big competitive field. Users are more attracted by a good QoS at the lowest price. Therefore, to attract more users and to gain more revenue, the service providers might decide to reduce price, this will also influence other service providers to review and reduce their prices as well.

2.6.1.2 Demand for a specific service

When the majority of users ask for a specific service and demand is high, the price that the service providers charge is affected. The more the demand for a specific service is high or low, the more the price of that service will increase and vice versa.

2.6.1.3 Cost of delivering a service

There are a certain number of costs that are incurred before a service is made available to customers. This cost must be included when a certain price is charged for a service.

2.6.1.4 Cost of spectrum

The cost of the spectrum is also assessed in a similar way, a given amount for the frequency spectrum is charged to each allocated country, this price is dependent on the deployment of spectrum.

2.6.2 Categories of pricing Schemes

The pricing schemes can be classified into two major categories known as flat-rate pricing schemes and parameter-based pricing schemes as illustrated in Figure 2.4.

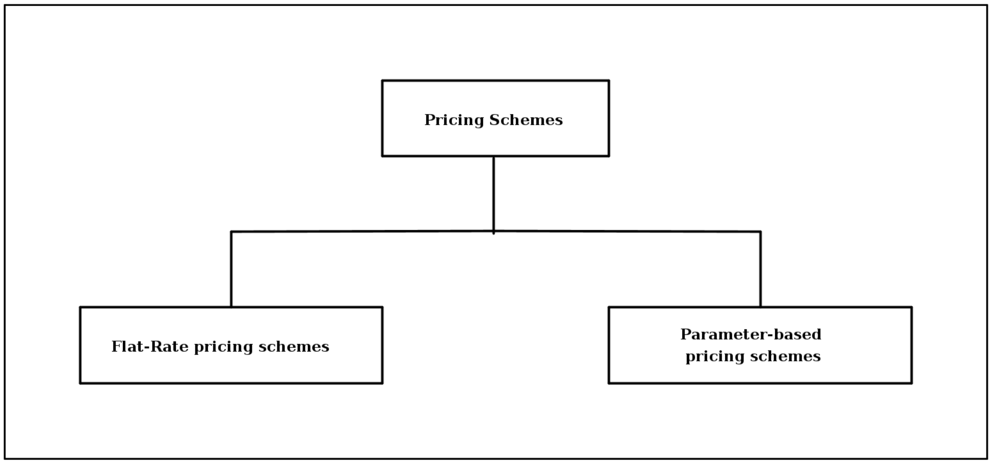

Figure 2.4: The two major categories of pricing schemes

2.6.2.1 The flat-rate pricing schemes

According to Gizalis and Vergados [40], the flat-rate pricing schemes were essentially used in previous years because of their minimal accounting overhead; they set a fixed price for each session without taking into account the condition of the network, as usage, network capacity, actual time the user can spend in the network or the type of services etc. The flat-rate pricing scheme does not accommodate any motivation to adjust demand by users, this is why other schemes have been proposed, for example, the parameter-based pricing schemes which could be discussed subsequently. There exists some examples of flat-rate pricing schemes, they are: metered pricing, packet pricing, time-based pricing, expected capacity pricing, volume-based pricing, paris-metro pricing, content-based pricing and market-based reservation pricing.

2.6.2.2 The parameter-based pricing schemes

The parameter-based pricing schemes address the disadvantages of the flat-rate pricing schemes as it is focused on what the service provider will do to increase the QoS offered to users in order to gain revenue and to increase the satisfaction of users when they receive services. The parameter-based pricing schemes take into account the condition of the network before charging their price and also seek to improve the adaptability, the credibility, flexibility and the resource allocation mechanisms [40]. They also permit the fulfilment of the users needs.

Gizelis and Vergados [40] distinguished between two categories of parameter-based pricing schemes known as the static and dynamic pricing schemes, this distinction is based on their flexibility to change while being used or their adaptability to various wireless technologies.

1. The static pricing schemes set the price in a static way meaning that, the users calls are charged with a predefined price for the services they use, regardless of the network resource variations, the available bandwidth of the network or the usage of the network resources, etc.

   This is inconvenient for the users in a case where the predefined price set is high, on the other hand, they could be charged a low price when the scheme considers the variations of network resources or the available bandwidths of the network.
   According to the method adopted by the pricing scheme used, the static pricing schemes are also classified as follows: adaptation pricing schemes [41], priority pricing schemes [42], cumulus pricing schemes [43] and broadcasting pricing schemes [44].

2. The dynamic pricing schemes allow the service providers to modify the users' services priority by considering the variation of the users' demand on the network. Gizelis and Vergados [40] note that service providers prefer to use dynamic pricing schemes because they are easily adaptable during the interconnection of the HWNs. In addition, this pricing scheme is also preferred by the users because users are able to select their preferable class of services and are thus charged accordingly. The dynamic pricing scheme can achieve load control by trying to avoid situation where load exceeds a certain limit in a given RAT, to prevent high interference situations [45]. The dynamic pricing scheme has been applied in multiple domains such as congestion control [46], admission control [47], power control [48] or pack scheduling [49].

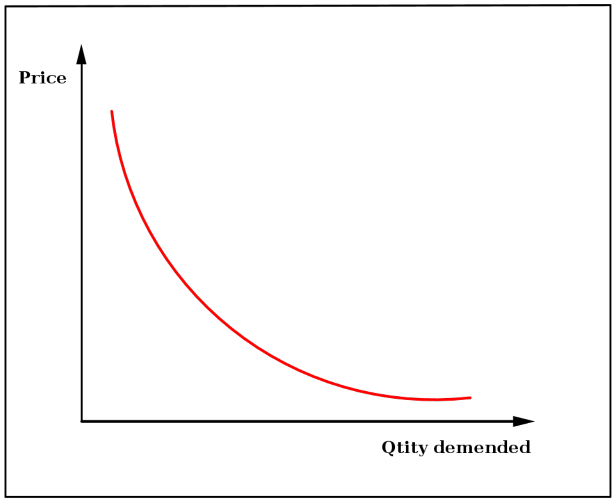

Figure 2.5: Demand curve

2.6.3 User price sensitivity

When price sensitivity is discussed, the price elasticity of demand is used, to give the measure of user, it is commonly used in economics to show the elasticity or the change in the quantity demanded for a good or service due to a change in its price. The price elasticity of demand can be defined as a measure of the relationship between the percentage change in the quantity demanded of a particular good and the percentage change in its price. The price elasticity of demand is used in telecommunication network to analyse users' behaviour [50]. This is determined via price variations by using the user's demand functions. The demand functions express user demand as a function of price.

2.6.4 Congestion pricing

According to Al-Manthari *et al.* [51], the design of any congestion pricing schemes depends on two crucial components:

- The behaviour of user demand, is a component that must be taken into account for any congestion pricing scheme because users react differently to prices, this means that some users are more price sensitive than others. Some of the research studies mentioned have developed different user demand models. Some of which represent user demands as an exponential function while others represent user demand as a utility function.

- Price functions which are functions that allow to determine how the price of services is calculated for bandwidth, unit of time or power.

Several congestion pricing schemes have been developed and proposed for wired networks (Internet), they include: smart-market congestion pricing [52], progressive congestion second pricing [53], proportional fair congestion pricing [54], [55], [56].

Falkner *et al.* [57] and DaSilva [58] have investigated these schemes on wired networks which differ in many aspects such as in price functions, demand functions, etc. Congestion pricing involves several aspects of networks including the wired networks, but more prominent in Wireless Cellular Networks (WCN) due to limited bandwidth, interference and user mobility [51].

Al-Manthari *et al.* [51] have done a survey on congestion pricing for WCN and this has been proposed to solve the congestion problem in WCN. Congestion pricing for WCN has been classified into two different categories that depend on the level at which users are charged and are namely:

- Admission level congestion pricing: In this case, the price for a bandwidth or a unit of time is determined only if the user initiates a call request and before that call is admitted to the system [51]. The price is fixed for the duration of the call and it depends dynamically on the network load. Two types of calls are distinguished at the admission level of congestion pricing namely new and handoff calls. New calls occur when users make new connection, and handoff calls occur when the user moves to another cell which is not his initial cell. The handoff calls are not charged as new calls are charged at admission level because handoff calls are already charged at their initial cell, thus they are not considered as new calls even when users moves from one cell to another [51].

- Power level congestion pricing aims to charge users according to their power consumption, this allows for the regulation of their usage of power in the network and also to control congestion [51]. Al-Manthari *et al.* [51] specified that categories schemes start to perform after the call is admitted and also while the call is being made, this implies that the price may vary according to the usage of power by users. As reported in [51], the power-level congestion pricing schemes are exclusively specific to code division multiple access-based networks due to the fact that these networks suffer from a degradation of their QoS due to the interferences caused by the power transmitted by users to BTS, either uplink or downlink. The power-level congestion pricing schemes have two rationale level as specified in [51]. Firstly, to provide monetary incentives to users in order to use the power in a rational way that will help to reduce interference and thus mitigating the congestion problem. Secondly, to save power and to increase the battery life of users' mobile terminals. At power level, congestion pricing serves as a power control function.

2.7 Related researches

Some researches have developed different ways of solving the congestion problem in networks by using dynamic pricing. They have considered the fact that pricing the services on the network will influence the behaviour of users in relation to the network resources.

2.7.1 Integration of CAC and dynamic pricing

CAC in itself cannot provide sufficient incentives for users to use the channels resources effectively and cannot also solve the congestion problem in wireless networks. The researches of Hou *et al.* [59] and Manaffar *et al.* [60] have investigated the integration between pricing and CAC in order to solve the congestion problem, such as when a specific price is charged for a call, users can influence their behaviours in the utilization of network resources.

Thus, the integration of pricing and CAC, as shown in [59], provide a new dimension for the design of CAC schemes which can also be used in wireless networks. Hou *et al.* [59] compares the performance of the integrated pricing scheme and CAC with the conventional system where pricing is not considered.

The problem can be defined as being the result of the selfishness of network users who monopolize the network resources for their individual satisfaction without considering the impact of that action on the total utility of the community at large thus in many instances, the congestion situation is not avoidable.

Hou *et al.* [59] and Manaffar *et al.* [60] reported that, in the case where the new call arrival rate is less than the optimal call arrival rate, this is a profitable case for the users because they can get better quality than the QoS required but it is not profitable for the service provider because some channel resources are wasted leading to less revenue for service providers. On the other hand, in the case where the new call arrival rate is greater than the optimal call arrival rate, a large number of users make calls at the same time and are blocked when they try to initiate their calls or to handoff to another cell during a call, leading to the degradation of the QoS.

Hou *et al.* [59] and Manaffar *et al.* [60] have the purpose of maximizing total user utility which means that the channel resources will be used effectively and the users will get a good QoS required from the service provider. Considering the integration of the pricing and call admission control, a system is required in which two blocks have to be considered:

- A pricing block which allows charging a specific price to users who want to make a call,
- A CAC block (uses guard channel scheme) which allows managing of the handoff calls such that some channels are reserved for handoff calls.

According to Manaffar *et al.* [60], the system function of pricing block is defined as a percentage of all the incoming users that will accept to pay the price at time t.

$$H(t) = \frac{\lambda_{in}(t)}{(\lambda_n(t) + \lambda_r(t))} \tag{2.7.1}$$

where λ_r is the call arrival rate of the users who decide to make their calls later, when the condition of network change and the price decreases [60]. As defined in [60], the price charged to users depends on the traffic load in the networks:

- When the new call arrival rate is less than the optimal call arrival rate or value ($\lambda_n < \lambda_n^*$), a normal price (which is acceptable to every user) is charged to each user [61].
- When the new call arrival rate is greater than the optimal call arrival rate or value ($\lambda_n > \lambda_n^*$), then a dynamic peak hour price is charged to users who want to make calls at that specific time. It is noteworthy that the system makes the decision about the fee charged at peak hour, this is not dependent on the time of the day but on the actual network condition.

The aim as previously stated, is to reduce congestion in the network by considering that users need to get a QoS and the service provider needs to generate sufficient revenue on the channel resource utilization, thus, the incoming user calls λ_{in} always have to meet the following requirement:

$$\lambda_{in}(t) \leq \lambda_n^* \tag{2.7.2}$$

This requirement prevents the congestion as the wastage of channel resources is avoided guaranteeing good quality of service to users.

2.7.1.1 Calculation of price according to traffic load

Users are sensitive to price, hence the monetary incentive can help to influence the way users make use of the resources of the network. As mentioned below, the system has to calculate the price to charge users when congestion occurs.

There is a demand function which describes the reaction of users to the change in price established by the system [60]. The demand function used is:

$$D[p(t)] = exp\left(-\left(\frac{p(t)}{p_0} - 1\right)^2\right) \tag{2.7.3}$$

where $p(t)$ is the price charged to users at time t and p_0 is the normal price. The demand function denotes the percentage of users that will accept the price charged at time t.

According to the definition of the system function of pricing block $H(t)$ and the demand function $D[p(t)]$, Hou *et al.* [59] and Manaffar *et al.* [60] discovered that:

$$H(t) = D[p(t)] \tag{2.7.4}$$

$$H(t) = \frac{\lambda_{in}(t)}{(\lambda_n(t) + \lambda_r(t))} \tag{2.7.5}$$

As we know:

$$D[p(t)] = exp\left(-\left(\frac{p(t)}{p_0} - 1\right)^2\right) \quad \text{and such that} \quad \lambda_{in} \leq \lambda_n^* \tag{2.7.6}$$

$$\text{we have} \qquad H(t) = \frac{\lambda_{in}(t)}{(\lambda_n(t) + \lambda_r(t))} \leq \frac{\lambda_n^*}{(\lambda_{in}(t) + \lambda_r(t))} \tag{2.7.7}$$

$$\text{then} \qquad D[p(t)] = \frac{\lambda_n^*}{(\lambda_n(t) + \lambda_r(t))} \tag{2.7.8}$$

$$p(t) = \frac{\frac{\lambda_n^*}{(\lambda_n(t)+\lambda_r(t))}}{D} \tag{2.7.9}$$

hence according to [59], [60] (2.7.10)

$$p(t) = D^{-1}\left(min\frac{\lambda_n^*}{(\lambda_n(t) + \lambda_r(t))}, 1\right) \tag{2.7.11}$$

So $p(t)$ is the price that should be charged to users to obtain the desired QoS.

2.7.2 Joint Call Admission Control

The traditional CAC determines a certain number of calls in the network, Manaffar *et al.* [60] defined CAC as: "a provisioning strategy used to limit the number of call connections in the network in order to reduce network congestion and provide desired QoS to users of services".

Some researches have integrated CAC and dynamic pricing to solve the problem of congestion in the wireless networks especially homogeneous wireless networks. Falowo*et al.* [62] present JCAC algorithms for HWNs as a technique responsible for deciding whether or not an incoming call may be admitted into a RAT and also to decide which available and suitable RAT it should be admitted into so that the incoming call of users may be accommodated. Figure 2.6 illustrate the basic functions of JCAC algorithms.

In HWNs, RAT has maximum load capacity or maximum coverage area. Some of the RATs are overloaded while others are under-utilized, leading to poor utilization of radio resources. Falowo*et al.* [62] have specified that managing the load-balancing of traffic among multiple RATs allows for better utilization of radio resources and this means that the users' preferences in making RAT selection decisions have to be considered in order to enhance user satisfaction, which means, users are able to set their different preferences for a particular RAT since their mobile devices, could be changed dynamically over time. There are different factors users take into account in determining their preferences. These are:

- Service price: Users take into account this factor because users prefer to be connected to a cheaper and available RAT such that service price varies in each RAT.

- Battery power consumption: Different RATs use different types of coding techniques and modulation, this implies a high consumption of battery power, thus, users prefer to be connected through RATs that minimize power consumption of mobile phone batteries.

- Data rate: This factor is important for users such that each RAT offers different data rates for different classes of services.

- Network security: Users prefer to be connected through RATs that have the highest security levels. The security level is usually specified by using linguistic values such as very low, low, medium, high and very high.

Suleiman *et al.* [32] have proposed JCAC algorithms for the HWNs which is divided into two algorithms, the Horizontal Call Admission Control (HCAC) and Vertical Call Admission Control (VCAC) that avoid unnecessary signalling and processing for certain stages of the JCAC that are specific to a RAT.

The HCAC algorithm function is similar to the traditional CAC with the goal to manage each

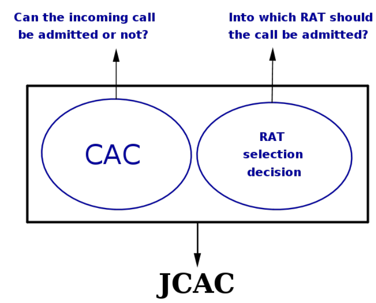

Figure 2.6: Basic functions of JCAC algorithms [62]

access network and to decide whether or not the admission of certain calls into the RAT would be done. Suleiman *et al.* [32] specify the case where there are multiple cells, HCAC in a cell has to share periodically the traffic information with other HCACs in neighbouring in order to predict future traffic conditions. However, VCAC algorithm is separated into three conditions which are:

- Call arrival which works as follows: When a new call arrives (voice or data), HCAC replies to a query by the VCAC about the traffic information and then VCAC decides which RAT is suitable to accept the call and also what the preference of each network is for the type of service request. In the case where there are multiple suitable RATs to accept the call, VCAC algorithms will make a random choice of one of the calls to admit.

- Necessary handoff, when the end user roams through the HWNs, there is sometimes the possibility that the RAT where the mobile terminal is connected, is not available at a given location, the HCAC algorithm will inform the VCAC algorithm of the situation and the VCAC algorithm will choose another best available RAT to admit this call.

- Desirable handoff, the VCAC algorithm has to always examine the report received from individual HCAC about the traffic information of the different RATs, nevertheless, there exists the case of load imbalance even if VCAC algorithms take into account the load balance admitting new calls. Thus, in this case, the VCAC algorithm has to decide to take some mobile terminals from the heavily loaded networks and try to connect them to slightly loaded ones only if the load imbalance reaches a certain threshold.

One can observe that the JCAC is the algorithm that helps in the selection of suitable RATs and that decides the admission of calls into the network by considering the network load and the users' preferences. More researches have been done on the JCAC algorithm and these produced gave good results [5] [10]. Falowo*et al.* [62] described their proposed JCAC scheme which contains four components, these components are described in the next subsection.

2.7.2.1 Joint call admission controller

Joint call admission controller implements the JCAC algorithm [62], meaning, it uses firstly, the fuzzy Multi-Attribute Decision Making (MADM) technique to select the most suitable RAT for each user. The joint call admission controller has two stages, the first stage consists of converting the fuzzy data into real-data, and the second stage, which is the classical MADM will be used to determine the ranking order of available RATs. Secondly, the joint call admission controller consists of the illustration of the RAT selection procedure by using single-class real-time calls [62]. Thirdly, it has to replace, for each RAT, the initial price with the new price calculated [62].

The joint call admission controller works in the following way, the user makes a call, where user requests for services to the joint call admission controller. These service request contains the call type which could be new or handoff calls, service class, minimum and maximum bandwidths required for this calls and weights assigned by the user to each of the RATs selection criteria. The decision made by the JCAC algorithm on the most suitable and available RAT for the incoming call is made on the basis of the service request information and then the JCAC algorithm will notify the mobile terminal user with this decision.

Assume, H is a set of available RATs, the response can be "call accepted" into RAT-$j \in H$ or "call blocked" into RAT-$j \in H$ for an incoming new call and "call accepted" into RAT-$j \in H$ or "call dropped" into RAT-$j \in H$ for an handoff call. Falowo*et al.* [62] have illustrated by using Figure 2.7, the assignment of weights to each of the RAT selection criteria for each class of calls (e.g. voice call, download, video call etc.) where the weights assigned to each criterion

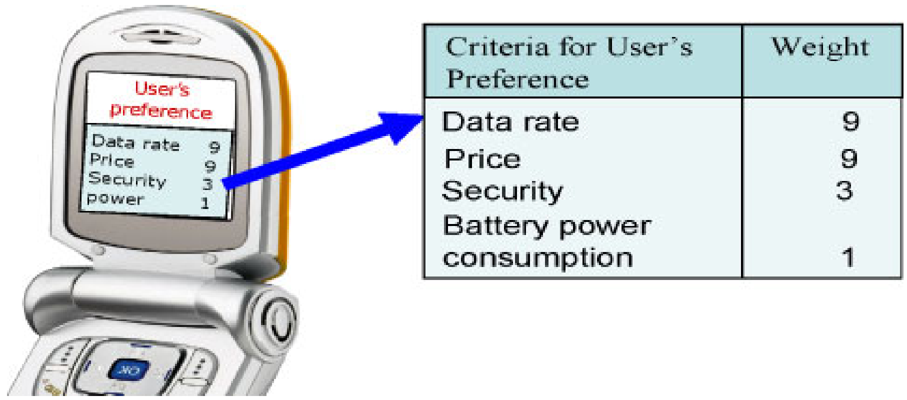

Figure 2.7: Weights assigned to each of the RAT selection criteria [62]

are known to users and are on standard scales, e.g. the weight can be on a 10 points scale (0 - 10) where 0 represents the minimum weight and 9 the maximum weight. The subscribers assign weights to the RAT selection criteria, not to the RATs. The assignment of weights constitutes the relative significance of each of the RATs' selection criteria to each user [62].

Fuzzy MADM method selection in JCAC algorithm

The fuzzy MADM method selection is used in the JCAC algorithm to select the most suitable RAT for each user.

The JCAC algorithm first states the fuzzy MADM problem, where there is a set Y alternative RAT-j (with $j = 1, 2, ..., Y$), which have to be evaluated for each incoming call with respect to a set of N criteria, where they are independent of each other. Zhang [63] and Falowo*et al.* [62] specified that a decision problem may be briefly expressed using a decision matrix M where the capabilities of Y alternative RATs and N criteria is given as:

$$M = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,N} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{Y,1} & c_{J,2} & \cdots & c_{Y,N} \end{bmatrix}$$

where $c_{j,n}$ is the performance rating of RAT-j (j=$1, 2, ..., Y$) on criterion-n (n=$1, 2, ..., N$). As mentioned above and specified by Falowo*et al.* [62], a selection criterion used to determine the users' preferences for a particular RAT is the real number, whereas, another one is the linguistic value (e.g. power consumption: very low, low, medium, high, very high). The fuzzy MADM method is categorized into three types of groups which occur when: (i) data can all be fuzzy number, (ii) all crisp number and (iii) either crisp or fuzzy number, thus, the fuzzy MADM method with data type is completely fuzzy [63].

Zhang [63] specified that the disadvantages or problems of existing fuzzy MADM methods have been solved and, this was proposed by Chen *et al.* [64]. Their approach to solve these problems consist of two different phases, where the first consists of the conversion of fuzzy data to crisp numbers and the second consists of the application of the classical MADM to determine the ranking order of the alternatives [63].

In the case where fuzzy data are linguistic terms, firstly, they will be converted to fuzzy numbers by using a conversion scale, and secondly, the result will be converted to a crisp number [63]. The conversion will be done as follows: Assume we have 5 linguistic terms used to represent the possible users' preferences which are: very low, low, medium, high, very high [62], the first step is conversion into fuzzy number by using the conversion scale as has been done as shown in Figure 2.8, where both, the performance score x and the number-ship function are in the range of 0 to 1. There is a fuzzy scoring method used thereafter to convert each fuzzy number to a corresponding crisp value. Regarding the 5 linguistic terms mentioned above, their corresponding crisp number conversions are $0.091, 0.283, 0.5, 0.717, 0.909$, respectively. There exists different numbers of linguistic terms where Chen *et al.* [64] have described eight different conversion scales.

Normalization of the decision matrix

Falowo*et al.* [62] notified that in the case of fuzzy MADM problems, the selection of alternatives is made by the decisions makers and are associated with non-commensurate attributes. In

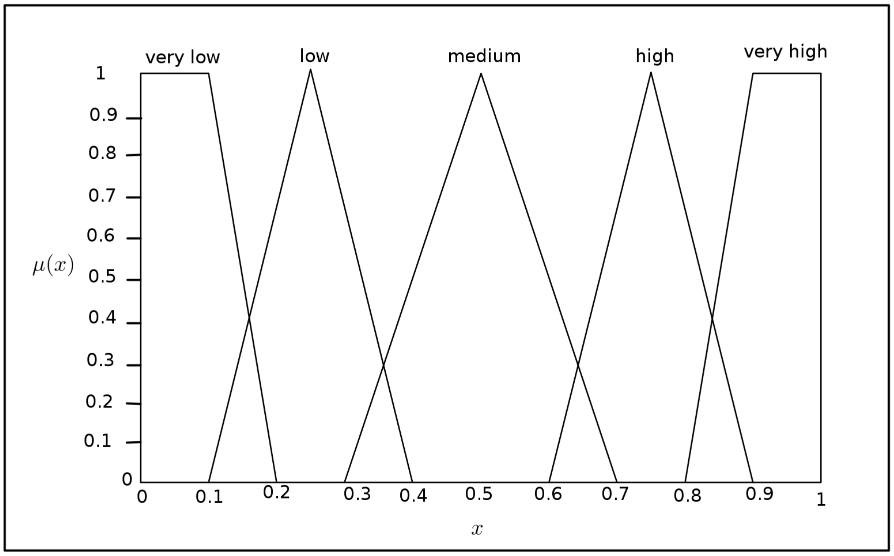

Figure 2.8: Linguistic terms to fuzzy number conversion scale [62]

addition the preference information of the decision-makers is often used in the ranking of alternatives that are the most desirable one [62]. There exists multiple classical MADM methods which are the following:

- Simple Additive Weighting (SAW method): Ravanshadnia *et al.* [65] specified that the overall score of an alternative in SAW is calculated as the weighted sum of all the attribute value.

- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS method): Ravanshadnia *et al.* [65] described this technique stating that: "TOPSIS is based on the principle that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative solution".

- Data Envelopment Analysis (DEA method): This was specified by Ravanshadnia *et al.* [65], DEA has acquired its popularity in solving decision problems for over a decade. The preferences among different attributes are not enabled, hence a user may not have influence on decision making [63], [65].

- Analytical Hierarchical Process (AHP method): This method allows one to develop a hierarchy objective that could help solve the decision problem with a large number of attributes [65]. This requires pairwise comparisons between alternatives for each attribute in each hierarchy and the consistency check, which could be too bulky for a user [63]. Zhang [63] specified that AHP is equivalent to the SAW when the hierarchy has only three levels.

Thus, after the conversion of linguistic terms to crisp numbers as developed above using one of the methods prescribed by Chen *et al.* [64], the next step is the ranking of alternatives by using one of the MADM methods referred to above. Zhang [63] has compared the different MADM methods for ranking voice and download applications and has specified that SAW and TOPSIS are the most simple and easiest to understand. The conclusion summarized by Zhang [63] on these methods illustrated their different performances. Such that SAW is probably the most widely used method, Falowo*et al.* [62] used this in their research study. The SAW method requires the normalization of the decision matrix M. There are two different criteria in solving the MADM problem which are the benefit and cost criteria. Normalization is necessary in order to measure all criteria without any dimensions and also to facilitate their comparison in case where the dimensions of each criteria is different. Falowo*et al.* [62] have normalized the value criteria by calculating each normalized value $b_{j,n}$ of the normalized decision matrix $\bar{M}$ as follows:

$$b_{j,n} = \begin{cases} \dfrac{c_{j,n}}{\max\{c_{j,n}|j = 1,2,...,Y\}} & \text{for benefit criterion } c_n \\ \dfrac{\min\{c_{j,n}|j = 1,2,...,Y\}}{c_{j,n}} & \text{for cost criterion } c_n \end{cases}$$

where $b_{j,n}$ is the normalized performance rating of RAT-j on criterion-n, $j = 1,2,...,Y; n = 1,2,...,N$. The preference information which is provided by each user for a specific RAT for each class of calls is modelled as the weight attached to each network criterion by the user. A weighted vector as defined by Falowo*et al.* [62] as W_c^i represents the relative importance of the criteria to user-c of class-i, it is expressed as follows:

$$W_c^i = (w_1, w_2, ..., w_N) \tag{2.7.12}$$

The weighting vector has to be normalized as:

$$W_c^i = (w_1, w_2, ..., w_N) \tag{2.7.13}$$

$$W_c^i = \frac{w_i}{\sum_{i=1}^{N} w_i}, \quad with \quad i = 1, 2, ..., N \tag{2.7.14}$$

The relative importance of each criterion to users is shown by the weight. As specified in [62], the normalized weighing vector (W_c^i) and the normalized decision matrix (M_0) are both used to rank the alternative RATs for each arriving class$_i$ call. The selection of the most appropriate RAT for the incoming calls is usually based on two different preferences: strict and flexible preferences. In the case of the flexible preference, an incoming call is admitted into the RAT that has the highest ranking and enough bandwidth to accommodate that call, if the highest ranking RAT cannot accommodate the call, the call will be admitted into the next highest ranking RAT and so on. Falowo*et al.* [62] specified that the call will be blocked only if all the available RATs do not have enough resources to accommodate the call. In the case of the strict preference, the incoming call is admitted into the RAT which has the highest ranking and enough bandwidth to accommodate it, if the highest ranking RAT does not have enough radio resources, the call will blocked.

2.7.2.2 CAC rate measurement unit

The CAC rate measurement unit consists of the measurement of the arrival rate and the residual capacities of different classes of calls in each RAT [62]. The measurement is done periodically.

2.7.2.3 Price-update unit

The price-update unit consists of the periodically adjustment of service pricing in each RAT in the HWNs. Information about the residual capacity available in the network and also the mean call admission rate in each RATs is obtained from the CAC rate measurement unit [62].

2.7.2.4 Bandwidth reservation unit

The bandwidth reservation unit known as the CAC scheme reserves some channels for handoff calls, JCAC algorithms also reserve certain bandwidths only for handoff calls in all the cells of each group of co-located cells so as to maintain a lowers dropping probability.

Some other JCAC algorithms do not consider that an analytical model has to be developed to study connection-level QoS in HWNs, this leads to highly unbalanced traffic among available RATs, such that users act independently [62]. The highly unbalanced traffic in turn leads to high overall call blocking and dropping probabilities and this will result in the poor utilization of radio resources in HWNs.

2.8 Summary

This chapter has given an overview of background information and literature on different concepts, methods and techniques used in HWN. Some challenges of NGWNs, RRM techniques have also been discussed. The JCAC algorithm is discussed highlighting its benefits, requirements and the RAT selection approaches. Network congestion was presented with detailed explanations of congestion collapse, congestion avoidance and TCP congestion control. Also, the pricing scheme approach was explained in addition to factor of pricing, categories of pricing schemes, user pricing and congestion pricing in view of their developments over the years as presented in literature. Related Research on the dynamic pricing scheme integrated with the CAC, and the JCAC algorithm was also investigated.

Chapter 3

Analytical model

This chapter describes the congestion that occurs during the peak hours of the day where an analytical model is utilised for a SCJCAC algorithm with the multi-dimensional Markov process model. Two recent dynamic pricing schemes are investigated in literature as possible ways or methods to reduce congestion in HWNs.

3.1 Traffic congestion

The peak hour or rush hour is the part of the day during which traffic congestion on the network is at its highest. In the peak hour periods, the demand for the use of the network increases in each RAT, leading to congestion. By considering the congestion that might occur during the peak hours of the day, a dynamic pricing scheme has to be elaborated upon in order to reduce this congestion by giving necessary incentives to users. Falowo *et al.* [62] specified that during the peak hours of the day, the service price may be increased compared to the off peak period. Therefore, users who do not have urgent calls can postpone their calls to the off peak period to reduce congestion. Assuming that in the peak period, during congestion time, the price increase depends also on demand in each RAT which helps to deter additional users from accessing the network or holding (maintaining) the resources of the network for a long period.

3.2 Service Class-based JCAC algorithm

The SCJCAC algorithm works by admitting different calls into particular RATs corresponding to the class of the service such as voice, data, streaming, video, etc. The SCJCAC algorithm is based on the fact that different RATs are optimized in order to support different classes of services, this means that RATs such as GPRS, support more voice services while, UMTS support data services, etc.

NGWNs comprise different types of RATs with varied capacities which can support different classes of services. By considering the peak hours of the day, the SCJCAC algorithm has to select the most suitable RAT for the incoming calls based on the class of services. During the peak hour period, some classes of services are in more supply than those of others, which means, that some RATs will be more congested than others. However there are some RATs which can support several classes of services. In accordance with this, in case of congestion during the peak hour period, the SCJCAC algorithm can prioritize the selection of the different classes of services which are in more supply into the RATs that can support them, while other classes of services which are not supplied into the RATs can support any or several classes of services.

In addition, RATs have specific capacities which makes them differ from each other. The RATs that can support several classes of services should have bigger capacities than others, to accommodate the classes of services that are not in large supply when congestion occurs during peak hour periods.

3.2.1 Resource sharing between voice and data

As NGWNs are expected to support multiple classes of services, Tzeng [66] classified these classes of services into two types: real-time and non real-time traffic. In this research study, voice is considered as real-time traffic and data as non-real-time traffic. The network resources have to be shared between these two classes of services.

Real-time traffic (voice) requires transmission in real time and has some level of tolerance to packet loss thus it is delay sensitive. On contrary, non-real-time traffic (data) is delay insensitive but only tolerant to variations in transmission rates thus it requires very reliable transmission [35], [67]. On the other hand, when data is lost during a transmission, it is possible to retransmit the lost data, this is not the case for real-time traffic.

It is necessary to take into account the data transfer time if one consider that the download of web documents or transfer of data files are viewed as packet losses. This implies that the data transfer time depends on the file size and the bandwidth allocated to it [35], [67]. Therefore, the mean transfer time for data traffic should be bounded below a threshold. To achieve efficient sharing of total bandwidths between voice and data, voice traffic should be offered pre-emptive priority over data traffic since it is delay sensitive, thus borrowing an amount of data traffic bandwidth will allow it increase or meet its QoS requirement as specified by [35], [66], [67]. Thereafter, the remaining bandwidth can be dedicated to data traffic. Moreover, all bandwidths which are not used by current voice traffic should be shared equally by incoming data flows in order of their achievement of resource utilization [35]. Tzeng [66] has proposed a movable-boundary resource sharing between voice and data with adaptive applicability which differs from other movable-boundary schemes previously studied in such a way that voice traffic users (real-time) are able to borrow the channels allocated to data traffic users (non-real-time).

3.2.2 Interworking between GPRS and UMTS

GPRS/UMTS evoluted from the GSM networks. GPRS is a 2.5 mobile communication technology, it allows the mobile wireless service provider offer to their mobile subscribers, packet-based data services over GSM networks [68]. UMTS is a 3G mobile communication technology able to provide the WCDMA radio technology which offers a higher throughput, real-time service, end-to-end QoS, video communication, multimedia, voice and data services to mobile users. This two RATs: GPRS/UMTS comprise two different network elements: Gateway GPRS Support Node (GGSN) which has the aim of providing mobile users with access to a Public Data Network (PDN) or to specify the private IP networks and the serving GPRS Support Node

(SGSN) which aims to connect the Radio Access Networks (RAN) to the GPRS/UMTS core. The SGSN seeks to:

- Tunnel user sessions to the GGSN,
- Send data to and receive data from the mobile station,
- Maintain all the information about the location of each mobile station,
- Communicate directly with the mobile station and the GGSN.

As specified in [68], 2.5G environment which is the RAN, comprises the mobile stations that are connected to a BTS and the BTS is connected to a BSC. However, the 3G environment which is the RAN, comprises mobile stations that are connected to a Node B and Node B is connected to a Radio Network Controller (RNC). The RAN connects to the GPRS/UMTS core through a SGSN [68]. The SGSN tunnels are sessions of a GGSN which acts as a gateway to the service networks. Besides, the GPRS Tunnelling Protocols (GTP) enables the connection between SGSN and GGSN.

In addition, GPRS offers close coupling between voice and data calls, which means during a data session, users can accept incoming voice calls, that will suspend the data session and resume it automatically when the voice calls end [69]. Likewise, users can also receive SMS messages and data notifications while receiving a voice call. The UMTS performs in the same way and has the benefits of high spectral efficiency for voice and data calls.

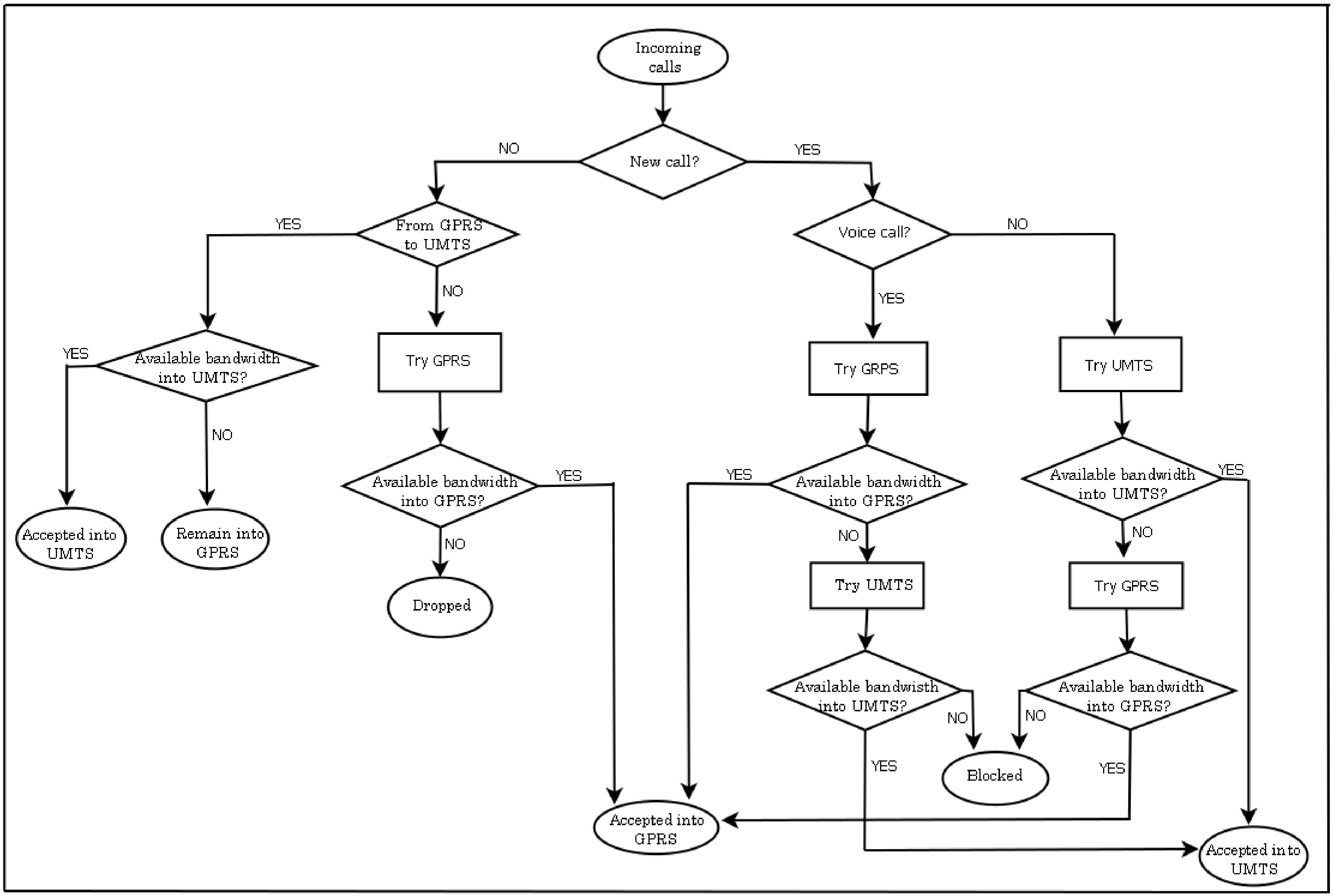

Figure 3.1: The SCJCAC algorithms

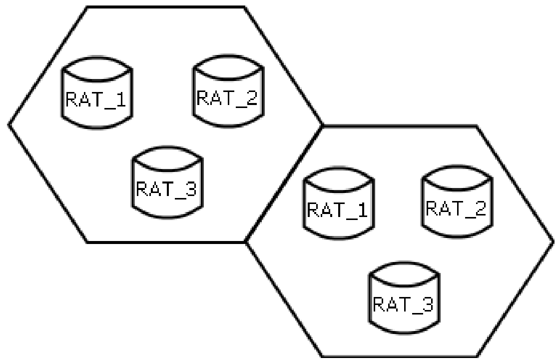

Figure 3.2: Heterogeneous network environment

3.2.3 Heterogeneous network environment

NGWNs are heterogeneous networks containing multiple RATs and that support multiple service classes, let X and Y represent the total number of services that can be supported by the RATs and the total number of RATs in HWNs respectively. Considering a given coverage area of HWNs which have multiple RATs denoted by RAT-j where $j = 1, 2, ..., Y$. One can observe that each RAT-j has a certain maximum amount of radio resources which represents its available capacity of coverage that it can provide. The coverage capacity that RATs provide is considered in terms of the basic bandwidth unit (bbu). Each RAT is assumed to have its maximum amount of bbu, denoted as B_j, the total amount of capacity in the network is the summation of the available capacity in each RAT, denoted as B_{total}, thus:

$$\begin{aligned} B_{total} &= B_1 + B_2 + ... + B_Y \\ &= \sum_{j=1}^{Y} B_j \end{aligned}$$

As mentioned above, NGWNs will support multiple classes of services in accordance with the RATs. Considering that each RATs can support different classes of services which can be denoted as class-i where $i = 1, 2, ..., X$.

Depending on the type of service as well as the QoS that is to be offered, the bandwidth requirements have to be pondered upon. This will vary from one service class to another and depends on the type of service. A call in a given class-i will require a given amount of bbu. Taking into account a cell that has a total capacity of bbu and two types of calls sharing the bandwidth of the cell namely the new and handoff calls. The arriving calls at the cell are partitioned into K separate classes based on the bandwidth requirement. The number of bbu required to accommodate the calls is given by b_k. The classes are indexed in an increasing order according to their bandwidth requirements, such that:

$$b_1 \leq \cdots \leq b_i \leq b_{(i+1)} \leq \cdots \leq b_k. \tag{3.2.1}$$

Let B_{ij}^n and B_{ij}^h denote the total bbu available in RAT-j for new class-i calls and handoff class$-i$ calls respectively, α_{ij} denotes the fraction of bbu available in RAT-j over the summation of bbu available in all RATs for new class-i calls and the corresponding value for handoff class-i is β_{ij}, then:

$$\alpha_{ij} = \frac{B_{ij}^n}{\sum_{j=1}^{Y} B_{ij}^n} \qquad \forall i \tag{3.2.2}$$

$$\sum_{j=1}^{Y} \alpha_{ij} = 1 \qquad \forall i \tag{3.2.3}$$

and similarly;

$$\beta_{ij} = \frac{B_{ij}^h}{\sum_{j=1}^{Y} B_{ij}^h} \qquad \forall i \tag{3.2.4}$$

$$\sum_{j=1}^{Y} \beta_{ij} = 1 \qquad \forall i \tag{3.2.5}$$

3.2.4 Splitting of the arrival process

Calls arrive into a group of cells and the SCJCAC algorithm selects the least loaded of the available RATs for all incoming calls. This process of selecting an appropriate and available RAT for each new or handoff call in the group of cells, as illustrated in Figure 3.3, leads to the splitting of arrival process.

Assume λ_i^n and λ_i^h are the arrival rates of new class-i and handoff class-i calls, into the group

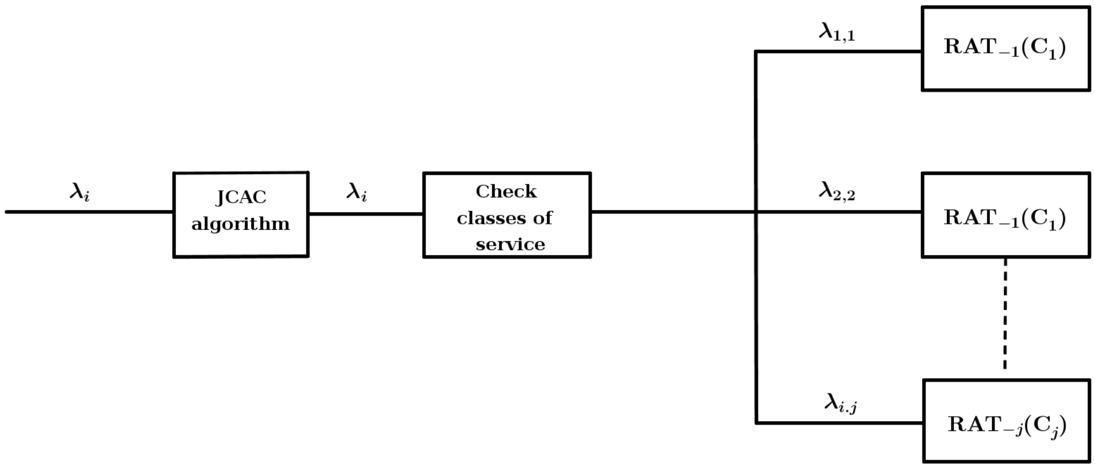

Figure 3.3: SCJCAC algorithm

of cells respectively. Furthermore, assume λ_{ij}^n and λ_{ij}^h are the arrival rates of new class-i and handoff class-i calls, into RAT-j respectively. Each RAT has a fraction of the new or handoff arrival rate and this presumes that:

$$\lambda_{ij}^n = \alpha_{ij} \times \lambda_i^n \tag{3.2.6}$$

$$\lambda_{ij}^h = \beta_{ij} \times \lambda_i^h \tag{3.2.7}$$

$$\lambda_i^n = \sum \lambda_{ij}^n \qquad \forall i \tag{3.2.8}$$

$$\lambda_i^h = \sum \lambda_{ij}^h \qquad \forall i \tag{3.2.9}$$

This research study presupposes that the arrival rate of class-i into the group of cells is a Poisson distribution and the arrival rates of class-i into the available RAT-j is also a Poisson distribution such that the arrival rates of a split are also Poisson distribution [70], [71].

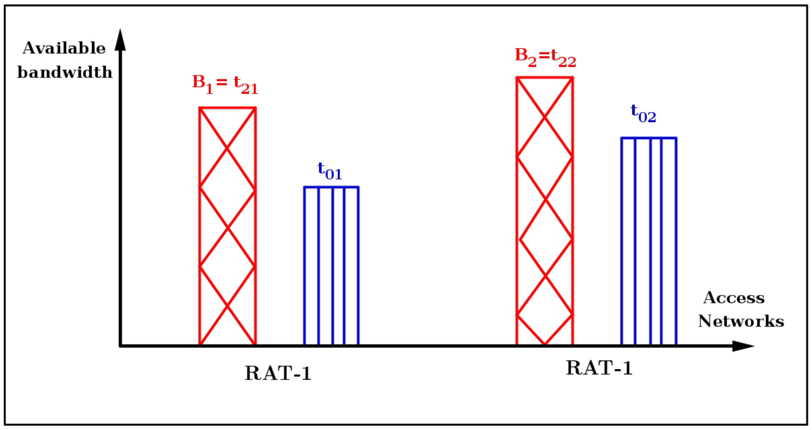

Figure 3.4: Bandwidth reservation policy for two RATs with two classes of services.

3.3 Bandwidth reservation policy

3.3.1 Description of threshold-based bandwidth reservation policy

In order to maintain a lower handoff dropping probability, a certain bandwidth only for handoff calls is reserved by using the threshold-based bandwidth reservation policy. This means that the bandwidths are reserved to aggregate exclusively handoff calls that have priority over new calls. In addition, the policy prioritizes between the different classes of handoff calls according to their QoS constraints by assigning a series of bandwidth thresholds T_{oj}, T_{1j}, T_{kj} such that:

$$T_{oj} \leq T_{1j} \leq \cdots \leq T_{ij} \leq T_{(i+1)j} \leq \cdots \leq T_{kj} = B_j \qquad \forall j \tag{3.3.1}$$

where T_{oj} denotes the maximum number of total bbu that can be allocated to new calls, T_{ij}, $1 \leq i \leq k$, denotes the maximum number of total bbu that can be allocated to class-i handoff calls in RAT-j. By considering the case where we have two RATs, GPRS and UMTS, with two classes of services, voice and data, the bandwidth reservation policy for this two RATs and the two classes of services can be illustrated in Figure 3.4.

3.4 Markov chain model

The analytical model can be classified into state-space models and non-state-space models. The Markov chain model most commonly used is the state-space model for analytical models such that, it helps to analyse and to model a performance and reliability analysis [72]. The Markov chain model used in this study consists of a set of states and a set of labelled transitions between these states.

3.4.1 Channel holding time and traffic intensity

By considering the resource management of the network, the new and handoff calls compete for resources in the air interface. Handoff calls require the reservation of some bandwidth which is called guard channels for handoff calls. The guard channels have to maintain high resource utilization and give higher priority to handoff calls causing the call dropping probability to reduce. The Markov chain model considers two parameters: channel holding time, which is related to the duration of a call and which is assumed to be exponentially distributed, and traffic intensity ρ, which is the ratio of the mean arrival rate to the mean service rate. Let μ_i denote the mean service rate for class_i calls. The call holding time or service time D_i for class_i calls can be expressed as:

$$D_i = \frac{1}{\mu_i}$$

3.4.2 The M/M/m/m queuing model

The M/M/m/m queuing model allows one to define the call arrival distribution in telecommunication systems. The Markov decision process constitutes the fundamental theory underlying the concept of queuing models [72]. The call arrival rate in M/M/m/m queuing model is assumed to follow a Poisson distribution while the service rate follows an exponential distribution. The number of resources available in the system is limited and the system can only support a maximum number of calls, this implies that the number of arriving calls into the system that exceed its maximum capacity are rejected.

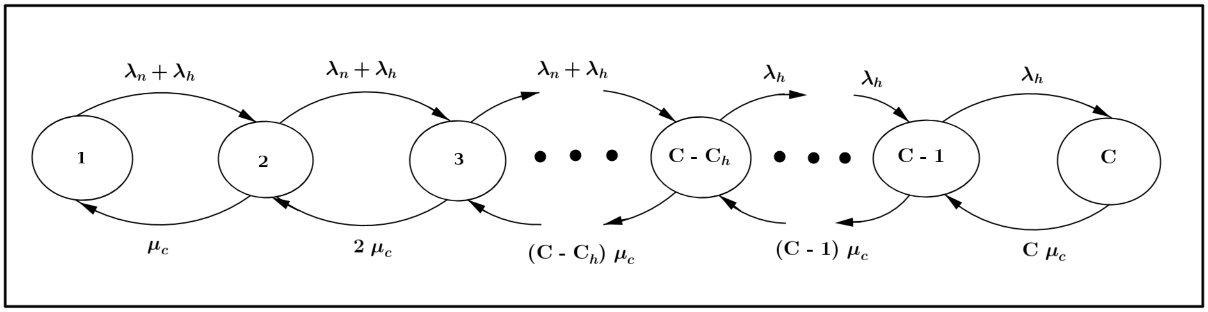

Figure 3.5: A one-dimensional Markov chain model

Let λ_n denote the new call arrival rate and λ_h the handoff call rate, with C representing the total channel on the system, C_h is the channel reserved for handoff calls and μ_c is the mean service rate for both new and handoff calls. The one-dimensional M/M/m/m state transition diagram is presented in Figure 3.5 above.

3.4.3 Multi-dimensional Markov model

The multi-dimensional Markov model has been found to be efficient in evaluating the JCAC algorithm in a NGWN such that it can employ different channel holding times for new and handoff calls.
Let λ_n and λ_h represent the arrival rate of new and handoff calls respectively with C being the total channels, C_h the channel reserved for handoff calls on the system, and μ_n and μ_c the service rates for the both new and handoff calls respectively. The state diagram for the two-dimensional Markov model is presented in Figure 3.6. The SCJCAC algorithm can be modelled as a multi-dimensional Markov chain. The state space of the heterogeneous system can be represented by row vector of (2*X*Y) components given as:

$$x = (m_{ij}, n_{ij}; i = 1, ..., X; j = 1, ..., Y).$$

The non-negative integer m_{ij} denotes the number of ongoing new class-i calls in RAT-j of the group of co-located cells and n_{ij} denotes the number of handoff calls of class-i in RAT-j of the group of co-located cells. Let S be the state space of all admissible states of the groups of

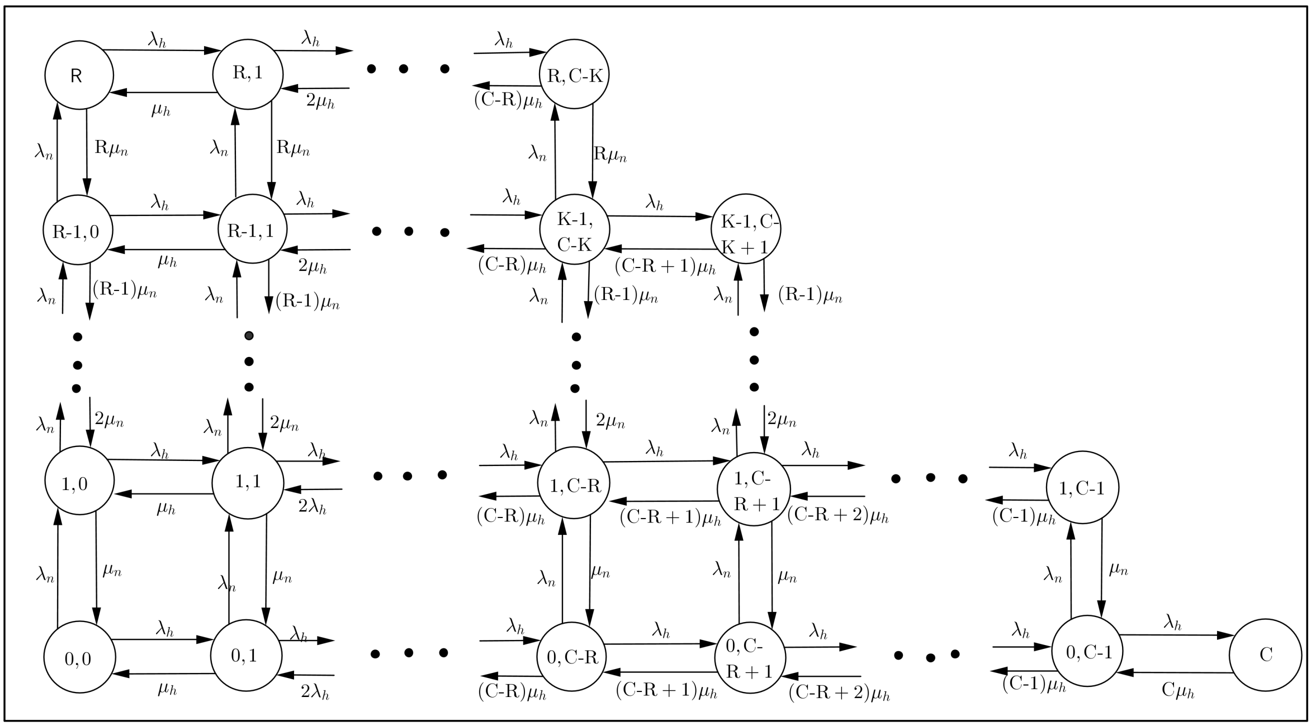

Figure 3.6: A two-dimensional Markov chain model

co-located cells as it evolves over time and s, an admissible state, which is a combination of the number of users in each class that can be supported simultaneously in the group of co-located cells while maintaining adequate QoS and meeting radio resource constraints.

A request for connection is sent to a group of co-located cells, at each time when new or handoff class-i of services arrive and JCAC decisions have to be taken upon arrival to decide whether or not to admit the call and in to which RAT it must be admitted. Therefore, the states of all admissible state as it evolves over time is represented as:

$$S = \left\{ x \in S : \bigwedge_{j=1}^{Y} \left(\sum_{i=1}^{X} m_{ij} b_i \leq T_{oj} \wedge \sum_{i=1}^{X} (m_{ij} + n_{ij}) \leq B_j \wedge \bigwedge_{i=1}^{X} n_{ij} b_i \leq T_{ij} \right) \right\} \qquad (3.4.1)$$

$$\text{where} \quad i = 1, 2, \cdots, X \quad \text{and} \quad \bigwedge_{k=1}^{Z} d_k = d_1 \wedge d_2 \wedge \cdots \wedge d_Z$$

d_k is an arbitrary variable to illustrate the meaning of the operation $\bigwedge$. T_{oj} is the threshold for all new calls in RAT-j. T_{ij} is the threshold for all handoff calls of class-i in RAT-j and after which handoff calls will be rejected in RAT-j. B_j is the total bbu available and RAT-j. b_i is the bandwidth allocated to class-i calls in RAT-j.

An accept/reject decision has to be made for each type of possible arrival in the group of co-located cells when the system is in state s and for the arrival of new or handoff class-i call. Thus, the call admission action space which is A can be expressed as follows:

$$A = \{a = (a_{n1}, ..., a_{nX}, a_{h1}, ..., a_{hX}) : a_{ni}, a_{hi} \in \{(0, 1, ..., Y), i = 1, ..., X\}\}$$

where a_{ni} denotes the action taken on arrival of new class-i call within the group of co-located cells and a_{hi} denotes the action taken on arrival of handoff class-i calls from an adjacent group of co-located cells. When $(a_{ni} \ \ or \ \ a_{hi}) = 1^j$, this means the new class-i call or handoff class-i call is accepted into RAT-1, and when a_{ni} or $a_{hi} = 0$, this means the new class-i call or handoff class-i call is rejected. So in the two classes of RATs in HWNs, the decisions of SCJCAC algorithm, $a_{n1}, a_{h1}, a_{n2}, a_{h2} \in$ (0,1,2) has priority effect.

Considering the Markovian property, the SCJCAC algorithm can be modelled as $(2 * X * Y)$ dimensional Markov chain, where $\rho_{new_{ij}}$ and $\rho_{han_{ij}}$ are considered as the load generated by new class-i calls and handoff class-i calls, respectively in cell RAT-j within the group of co-located cells, which are described as follows:

$$\rho_{new_{ij}} = \frac{\lambda_{ij}^{n}}{\mu_{n_i}} \qquad \forall i, j \tag{3.4.2}$$

$$\rho_{han_{ij}} = \frac{\lambda_{ij}^{h}}{\mu_{h_i}} \qquad \forall i, j \tag{3.4.3}$$

Then

$$d(s) = \prod_{i=1}^{k} \prod_{j=1}^{J} \frac{(\rho_{new_{ij}})^{m_{ij}} . (\rho_{han_{ij}})^{n_{ij}}}{m_{ij}! \; . \; n_{ij}!} \tag{3.4.4}$$

Let $P(s)$ denote the steady state probability that the system is in state $s \in S$ which is given by:

$$P(s) = d(s) \times \frac{1}{G} \tag{3.4.5}$$

where G is the normalisation constant given by:

$$G = \sum_{s \in S} \prod_{i=1}^{k} \prod_{j=1}^{J} \frac{(\rho_{new_{ij}})^{m_{ij}} . (\rho_{han_{ij}})^{n_{ij}}}{m_{ij}! \; . \; n_{ij}!} \tag{3.4.6}$$

3.4.3.1 Case study

By considering two classes of services, voice and data, and two RATs, GPRS and UMTS; the current state of the group of cells can be represented as:

$$x = \{m_{11}, m_{12}, n_{11}, n_{12}, m_{22}, m_{21}, n_{22}, n_{21}\}$$

New calls of class-1 (voice) are admitted into RAT-1 (GPRS) in priority and new calls of class-2 (data) are admitted into RAT-2 (UMTS) in priority. Handoff calls of the two classes are accommodated according to the RATs and according to previous accommodation of the two classes of handoff calls. So, the state of all admissible states as it evolves over time is represented as:

$$S = \Big\{ x \in S : (m_{11}b_1 + m_{21}b_2) \leq T_{o1} \wedge [(m_{11}+n_{11})b_1 + (m_{21}+n_{21})b_2] \leq B_1 \wedge n_{11}b_1 \leq T_{11}$$
$$\wedge\, n_{21}b_2 \leq T_{21} \wedge (m_{22}b_2 + m_{12}b_1) \leq T_{o2} \wedge [(m_{22}+n_{22})b_2 + (m_{12}+n_{12})b_2] \leq B_2$$
$$\wedge\, n_{22}b_2 \leq T_{22} \wedge n_{12}b_1 \leq T_{12} \Big\}$$

3.4.4 New call blocking probability

The new call blocking probability is considered as a probability that a new call is rejected by the JCAC algorithm. A new class-i call is blocked in the group of co-located cells if the call can not be admitted into the RAT-j by order of priority and into the RAT-$(j+1)$ by conventional order. Let S_{bi} denote the set of state where the new calls of class-i are blocked. Therefore, S_{bi} is given by:

$$S_{bi} = \left\{ s \in S : \bigwedge_{j=1}^{Y} (1 + m_{ij})\, b_i > T_{oj} \wedge \bigwedge_{j=1}^{Y} (1 + m_{ij} + n_{ij})\, b_i > B_j \right\} \tag{3.4.7}$$

$$\text{where} \quad i = 1, 2, \cdots, X \quad \text{and} \quad \bigwedge_{j=1}^{Z} d_k = d_1 \wedge d_2 \wedge \cdots \wedge d_Z$$

Therefore, the blocking probability for new class-i calls in the group of co-located cells will be given by:

$$P_{b_i} = \sum_{s \in S_{bi}} P(s) \tag{3.4.8}$$

3.4.4.1 Case study

Considering two service classes of calls (voice and data) and two RATs that can accommodate the two classes of services (GPRS and UMTS). A new class-1 call is blocked in the group of co-located cell if the call cannot be admitted into RAT-1 by order of priority and RAT-2 by conventional order.

$$S_{b1} = \Big\{ s \in S : ((1 + m_{11})b_1 > T_{o1} \vee (1 + m_{11} + n_{11})b_1 > B_1)$$
$$\wedge\, ((1 + m_{12})b_1 > T_{o2} \vee (1 + m_{12} + n_{12})b_2 > B_2) \Big\}$$

A new class-2 call is blocked in the group of co-located cells if the call cannot be admitted into RAT-2 by order of priority and RAT-1 by conventional order.

$$S_{b2} = \Big\{ s \in S : ((1 + m_{22})b_2 > T_{o2} \vee (1 + m_{22} + n_{22})b_2 > B_2) \\ \wedge ((1 + m_{21})b_1 > T_{o1} \vee (1 + m_{21} + n_{21})b_1 > B_1) \Big\}$$

3.4.5 Handoff call dropping probability

The handoff call dropping probability is considered as a probability that a handoff call is terminated or dropped by the JCAC algorithm.

A handoff class-i call is dropped in the group of co-located cells if the call cannot be admitted into RAT-j and RAT-$(j+1)$. Let S_{di} denote the set of states where the handoff calls of class-i is blocked. Therefore, S_{di} is given by:

$$S_{di} = \Big\{ s \in S : \bigwedge_{j=1}^{Y} (1 + n_{ij})\, b_i > T_{ij} \wedge \bigwedge_{j=1}^{Y} (1 + m_{ij} + n_{ij})\, b_i > B_j \Big\} \tag{3.4.9}$$

$$\text{where} \quad i = 1, 2, \cdots, X \quad \text{and} \quad \bigwedge_{j=1}^{Z} d_k = d_1 \wedge d_2 \wedge \cdots \wedge d_Z$$

Therefore, the dropping probability for handoff class-i calls in the group of co-located cells will be given by:

$$P_{d_i} = \sum_{s \in S_{di}} P(s) \tag{3.4.10}$$

3.4.5.1 Case tudy

Consider two service classes of calls (voice and data) and two RATs that can accommodate the two classes of services (GPRS and UMTS). A handoff class-1 call is dropped if the call can not be admitted into RAT-1 and RAT-2. S_{d1} denotes the set of states, in which a handoff class-1 call is dropped in the group of co-located cells, this is given by:

$$S_{d1} = \Big\{ s \in S : ((1 + n_{11})b_1 > T_{11} \vee (1 + m_{11} + n_{11})b_1 > B_1) \\ \wedge ((1 + n_{12})b_1 > T_{12} \vee (1 + m_{12} + n_{12})b_1 > B_2) \Big\}$$

A handoff class-2 call is dropped if the call cannot be admitted into RAT-2 and RAT-1. S_{d2} denotes the set of states, in which a handoff class-2 call is dropped in the group of co-located cells, this is given by:

$$S_{d2} = \Big\{ s \in S : ((1 + n_{22})b_2 > T_{22} \vee (1 + m_{22} + n_{22})b_2 > B_2)$$
$$\wedge ((1 + n_{21})b_2 > T_{21} \vee (1 + m_{21} + n_{21})b_2 > B_1) \Big\}$$

3.4.6 Users' utility function

The users' utility function can be defined as the users' level of satisfaction [9]. In other words, it is a decreasing function of new call blocking and handoff call dropping probabilities.
Let P_{bd_i} be a QoS metric for class-i calls that incorporate the new call blocking and handoff call dropping probabilities which is referred to as the preferred grade of service and is defined as:

$$P_{bd_i} = \beta P_{nb} + \gamma P_{hd} \tag{3.4.11}$$
$$(\beta + \gamma = 1 \quad \text{and} \quad \beta > \gamma)$$

where β and γ are weighted constants corresponding to new call blocking and handoff call dropping probabilities respectively. Niyato and Hossain [9] specified that P_{bd_i} is a function of new call arrival rate λ_n (e.g. $P_{bd_i} = f(\lambda_n)$). Let U_i be the users utility function for class-i call which is derived from [73] and is computed as follows:

$$U_i = \sum_{i=0}^{X} e^{-(P_{bd_i})} \qquad \forall i \tag{3.4.12}$$

Let U_{avg} be the average users' utility function in the system over a given duration T, which is computed as follows:

$$U_{avg} = \frac{1}{T} \left(\sum_{t=1}^{T} U_i \right) \tag{3.4.13}$$

3.4.7 Dynamic pricing scheme

In this section, a general illustration of the dynamic pricing scheme is given in Figure 3.7.

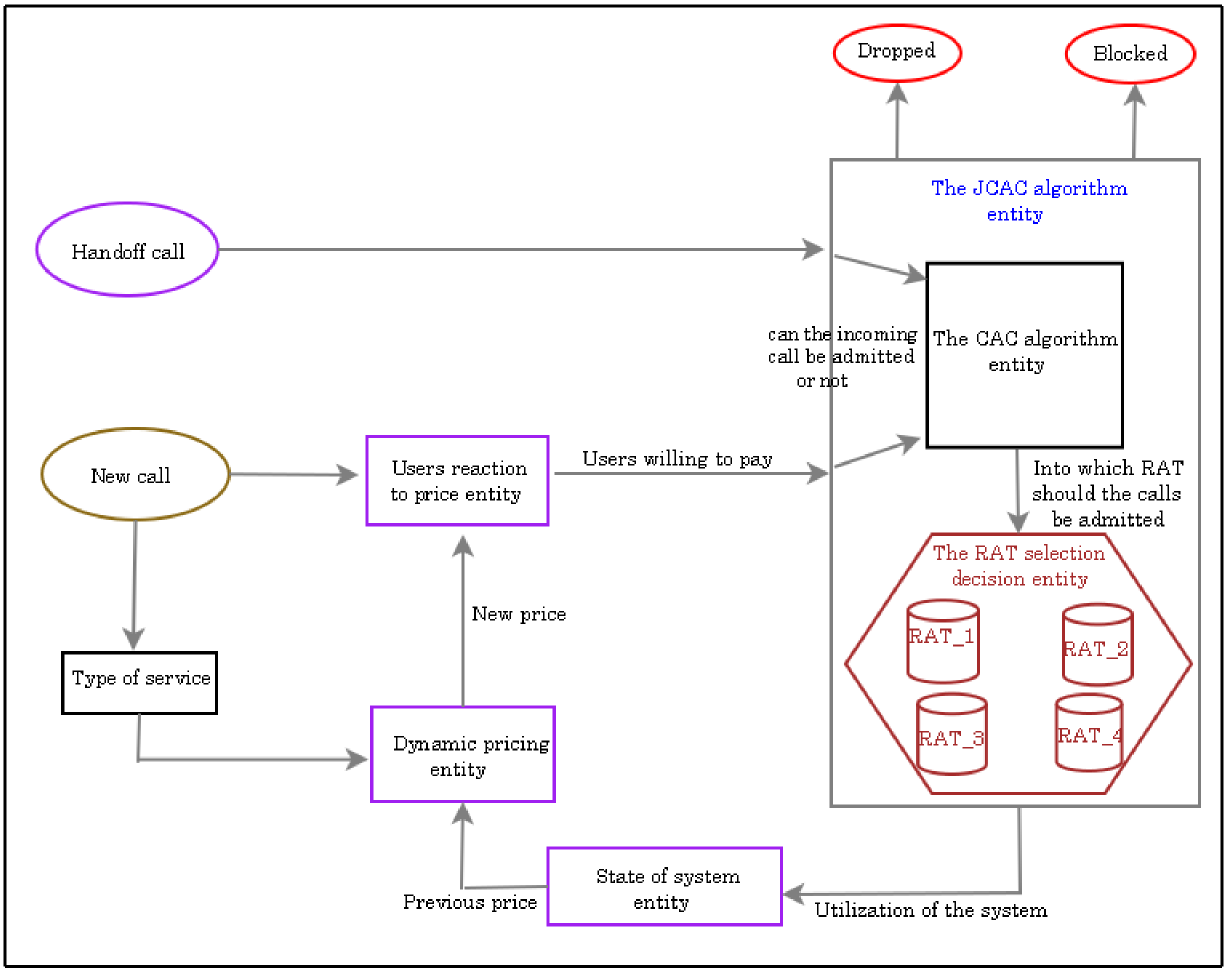

Figure 3.7: A general idea of dynamic pricing process

3.4.7.1 Dynamic pricing entity

The function of this entity is to calculate the new price to charge incoming users by considering the previous price and the utilization of the system. It receives the information on the state of the system such that in case of congestion, the entity sets the price based on the availability of RATs and the type of services of all incoming calls.

3.4.7.2 State of system entity

The state of system entity has the function of acknowledging the status of RATs and the previous price. This allows the system to know which RATs have more available bandwidth to accommodate the classes of services. This entity receives information from the JCAC algorithms entity about system utilization and transmits this information to the dynamic pricing entity for the computation of the new price.

3.4.7.3 Users' reaction to price entity

The users' reaction to the price entity reveals how users react to new prices charged by the dynamic pricing entity leading to users increasing or decreasing their demand for the network's services with respect to the price. At a low price, user demand will increase and at a high price user demand will decrease.

3.4.7.4 Type of services

The type of service entity would determine what service types the incoming calls apply such that the dynamic pricing entity requires this information to calculate the new price.

3.4.7.5 The JCAC algorithm entity

The JCAC algorithm entity is composed of two sub entities namely the CAC algorithm entity and the RAT selection decision entity that decides whether calls are blocked/dropped or admitted:

1. The CAC algorithm entity: The CAC algorithm entity has to verify if there is available bandwidth for the users willing to pay the price set by the dynamic pricing entity for the prescribed type of services before sending them to the RAT selection decision entity.

2. The RAT selection decision entity: The RAT selection decision entity receives the information from the CAC algorithm entity and decides which RATs the calls would be admitted according to the type of services and the availability of the bandwidth for each RATs. Moreover, the JCAC algorithm entity transmits information regarding the utilisation of such systems.

3.5 Investigation of dynamic pricing schemes

Two dynamic pricing schemes are investigated in different ways: dynamic pricing 1 proposed by Kabahuma and Falowo [5], henceforth referred to as DP1 and dynamic pricing 2 proposed by Falowo *et al* [62], henceforth referred to as DP2. A discount policy has been used to determine the new price per unit of time. This is aimed at encouraging or discouraging users' access to a network when there are underutilization or overloading conditions respectively. The new price can be computed according to the previous traffic intensity of the NGWN [5]. However, Al-Manthari *et al.* [74] specified that the new price is an inverse function of the percentage of users who are willing to pay for call requests to class-i. A maximum price per unit of time of class-i is considered P_{max_i}, which is charged to users when the planned upper limit of the system's capacity is reached. A positive scalar factor, say α, is used in the discount policy to represent a given level of discount. Kabahuma and Falowo [5] specified that the scaling factor α is predetermined by the network operator and depends on how much discount they are willing to offer their subscribers while the value can also be determined based on market forces. The discount offered for class-i calls denoted as DP_i is computed as follows:

$$DP_i = \alpha \times \left(\left(1 - \left(\frac{\sum_{j=1}^{Y} \left(\rho_{new_{i,j}} + \rho_{han_{i,j}}\right)}{\max\left(\sum_{j=1}^{Y} \left(\rho_{new_{i,j}} + \rho_{han_{i,j}}\right) \forall j\right)} \right) \right) \times P_{max_i} \right) \quad (3.5.1)$$

Let NP_{xi} denote the new price used in the system for class-i calls, NP_{xi} will then be computed as follows:

$$NP_{xi} = P_{max_i} - DP_i \quad (3.5.2)$$

Falowo *et al.* [62] considered a uniform distribution of load during any period T, which led them to consider an ideal arrival rate for new and handoff class-i calls in RAT-j, that are obtained as follows:

$$\bar{\lambda}^n_{ij} = \frac{\lambda^n_{ij}}{b_{ij}} \qquad \forall i, j \quad (3.5.3)$$

$$\bar{\lambda}^h_{ij} = \frac{\lambda^h_{ij}}{b_{ij}} \qquad \forall i, j \quad (3.5.4)$$

where λ^n_{ij} and λ^h_{ij} are as given in equations (3.2.6) and (3.2.7) respectively. Falowo *et al.* [62] actually described a dynamic pricing in two different functions namely, a linear price-update function and an exponential price-update function. The linear price-update function is calculated as follow:

$$P^i j, new = P^i_{j,old} + \Delta P_{ij} \quad (3.5.5)$$

while the exponential price-update function is calculated as follows:

$$P^i_{j,new} = P^i_{j,old} \times e^{\Delta P_{ij}} \quad (3.5.6)$$

$$P^i_{j,min} \leqslant P^i_{j,new}, \qquad P^i_{j,old} \leqslant P^i_{j,max} \quad (3.5.7)$$

where $P^i_{j,new}$ represents the new price per bbu of time for class-i calls in RAT-j and $P^i_{j,old}$ is the current price per bbu per unit of time for class-i calls in RAT-j. $P^i_{j,min}$ and $P^i_{j,max}$ are considered as the minimum and maximum prices per bbu per time in RAT-j respectively [62]. ΔP_{ij} is calculated as follows:

$$\Delta P_{ij} = z \times \left(\frac{\lambda_{ij} - \bar{\lambda}_{ij}}{\bar{\lambda}_{ij}} \right) \quad (3.5.8)$$

$$\text{where} \qquad \lambda_{ij} = (\lambda_{ij}^{n} + \lambda_{ij}^{h}) \qquad \text{and} \qquad \bar{\lambda}_{ij} = (\bar{\lambda}_{ij}^{n} + \bar{\lambda}_{ij}^{h})$$

ΔP_{ij} is described as the change in price per bbu per unit of time in RAT-j and z is a positive scalar step size. There are different types of step rules such as diminishing step size, increasing step size, constant step size. However, Falowo *et al.* [62] focused on the constant step size because of its simplicity.

3.6 Summary

This chapter has given an analytical model of the SCJCAC algorithm by using the multi-dimensional Markov process model and explained and investigated two recent dynamic pricing schemes.

Chapter 4

Analysis and numerical performance

This chapter illustrated the numerical performance of the analytical model discussed in the previous chapter. The performance of the two recent dynamic pricing schemes are discussed and they are compared with the flat-pricing scheme. The proposed SCJCAC algorithm is also evaluated in simulation.

4.1 System model

The simulation model applied for the HWNs consist of two RATs, Y=2, RAT-1 which is the GPRS and RAT-2 which is the UMTS. The RATs considered fully overlap. Two classes of services are considered, X=2, class-1 is the voice call and class-2 is the data call. Class-1 service call represents low bandwidth requirement while class-2 service call represents high bandwidth requirement. However class-1 puts a higher priority for admission into RAT-1 and a lower priority for RAT-2 while class-2 puts a higher priority for admission into RAT-2 and a lower priority into RAT-1. This caters for the bandwidth reservation policy where the threshold set for rejecting class-1 into RAT-2 is higher than rejecting class-1 from being admitted into RAT-1 and the threshold set for rejecting class-2 into RAT-1 is higher than rejecting class-2 into RAT-2. Presupposing that the arriving calls can be handoff calls or new calls. Higher priority is given to handoff calls than to new calls and this is reflected in the bandwidth reservation policy, therefore the threshold set for rejecting handoff calls is higher than the threshold set for rejecting new calls. To make a call, users have to decide if the price charged is appropriate. Users who agree to pay the charged price can make the call request. The SCJCAC algorithm will accommodate the call into RAT-1 or RAT-2 depending on the priority allocation of calls into the appropriate RAT and the load of each RAT. Call blocking and dropping will occur when the threshold set for new and handoff calls are exceeded.

4.2 Simulation environment

In this section, the environment used for the simulation of this research study is described. The details of the computer hardware are given below;

- The device name for the computer is Dell Vostro 3550.
- The memory is 3.8 GB.
- The processor is the Intel core i5-2450M CPU @ 2.50GHz $\times$ 4.
- OS type is 64 bit.
- The disk is 250 GB.

The details of the computer software used for simulation is the Ubuntu 12.04 utilised as the operating system. The implementation environment is the Gedit and the implementation language is PYTHON, some imported libraries such as Pylab, string, random, datetime, matplolib for plotting and math library are useful in the implementation of the mathematical functions.

4.3 Dataset for simulation

The dataset used for this simulation has been an estimation based on the demand distribution as described by Heegaard [75], [76] and Veloso *et al.* [77]. Heegaard [75], [76] specified that the data utilised in their research studies was extracted from Call Details Records (CDR) provided by the Norwegian IP telephony operator known as Telio and scaled hourly statistic from base stations provided by Norwegian mobile operator known as Netcom. The dataset used by Veloso *et al.* [77] was collected in Portugal and provided by Telecommunicações Móveis Nacionais (TMN) [78], one of the main telecommunication operators in Portugal. This dataset of call intensities was aggregated hourly for each cell with transformation procedures done by the service provider [77].

Data collected are anonymously done, as declared by Heegaard [75] in order to respect and protect the identity and position of the base stations. Furthermore, the factor used to scale the data is unknown in order to avoid revealing the details of the absolute traffic volume operators. Based on this information about the traffic intensity of calls during the day, Figure 4.1 shows the estimation of the demand distribution during the day, Heegaard [76] observed that users' demand increased around 10:00 am and decreased at 8:00 pm while Veloso *et al.* [77] specified that the mobile phone call intensity increases gradually around 9:00 am and decreases around 8:00 and 9:00 pm. Therefore, the assumption made in this thesis is that a congestion may occur between 10:00 am and 8:00 pm, during the day as illustrated in Figure 4.1.

4.4 Performance evaluation

In this section, the two previous dynamic pricing schemes [5], [62] are evaluated in simulations. The blocking / dropping probabilities for the two dynamic pricing schemes are evaluated and compared with the flat pricing scheme such that flat pricing is assumed to be the price used to estimate the traffic intensity illustrated in Figure 4.1. DP1 and DP2 have been integrated with the load-based JCAC algorithm in simulation which consists of the uniform distribution of traffic load among all the available RATs (2.4.3.2). The user utility is evaluated for DP1, DP2 and flat pricing to observe the level of satisfaction that users derive. The proposed flexible SCJCAC algorithm is evaluated to distribute classes of services into appropriate RATs by considering the increasing arrival rate of calls into HWNs and during the congestion period. Each evaluation is made for voice, data and both calls. The SCJCAC algorithm is used with

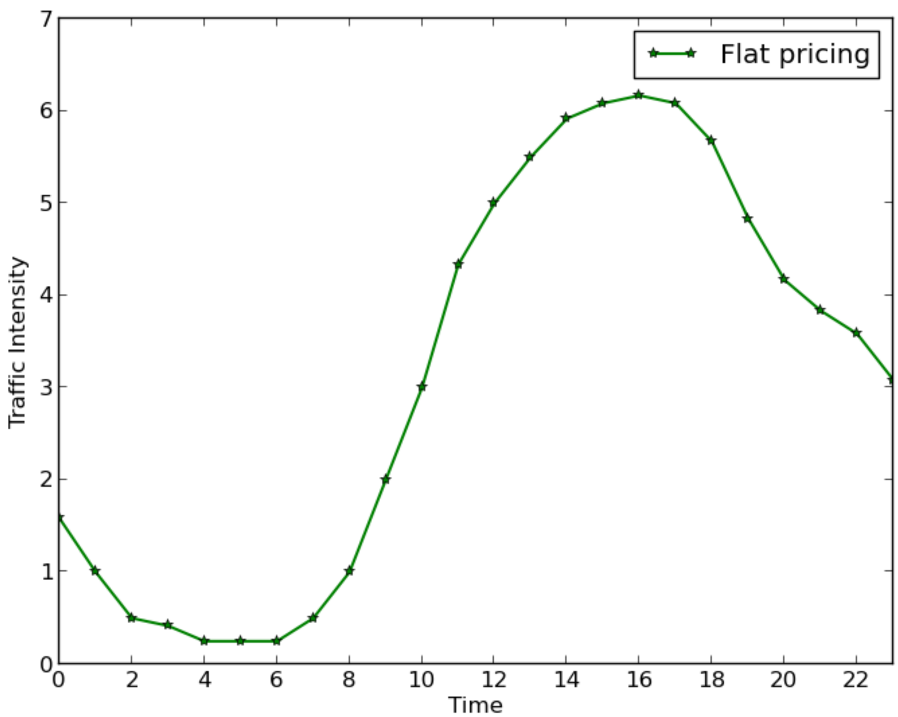

Figure 4.1: The traffic intensity during the day based on [75], [76], [77]

DP1 to reduce congestion during the day such that DP1 gives incentives to make the call while the SCJCAC algorithm distributes user calls for those who accepted to pay the charged price into the appropriate RAT. Moreover, the user's utility is evaluated for each class of services to observe users' level of satisfaction. An estimated demand distribution presented in [75] and [76] was determined since 2005 while in [77] it was determined since 2009. This depicts the characteristics of user behaviour.

The system parameters used in simulation for dynamic pricing and the SCJCAC algorithm are: $B_1 = 80$, $B_2 = 75$, $b_1 = 2$, $b_2 = 3$, $T_{o1} = 25$, $T_{o2} = 30$, $T_{11} = 50$, $T_{12} = 35$, $T_{22} = 45$, $T_{21} = 30$, $\mu_1 = 1$, $\mu_2 = 1$, $\max(\lambda_{ij}^n, \lambda_{ij}^h) = 7$, $\beta = \frac{1}{3}$, $\gamma = \frac{2}{3}$, $h = 0.5$, $\lambda_1^n = \lambda_2^n = \lambda$.
The arrival rate of handoff class-i calls is assumed to be proportional to the arrival rate of new class-i by:

$$\lambda_i^h = \frac{h}{\mu_i}\lambda_i^n \tag{4.4.1}$$

where h is the handoff rate. This is considered for the blocking and dropping probabilities according to arrival rate of calls.

The parameters used in simulation for the DP1 and DP2 as in [5], [62] are:
$P_{min_1} = P_{min_2} = 0$, $P_{max_1} = P_{max_2} = 2.5$, $\alpha = 1.0$
$P_1^{old} = P_2^{old} = 2.0$, $z = 1$, $\varphi_{j,min}^1 = 0.2$, $\varphi_{j,max}^1 = 5.0$

A brief and clear definition of these system parameters used for simulation are presented in Table 4.2.

4.5 Variation of call arrival rate

As Figure 4.1 shows, 10:00 am and 8:00 pm are considered as the highest usual business hours. In this period, the network is frequently utilised and user demand is at its highest level.

Figure 4.2 shows the traffic intensity with DP1, DP2 and the flat pricing. During the period

Table 4.1: Definition of the system parameters used for simulation

System parameters for HWNs	
Parameters	**Definition of parameters**
B_1, B_2	Total bbu available in cell of RAT-1 and RAT-2 respectively.
b_1, b_2	Bandwidth requirements for class-1 and class-2 calls respectively.
T_{o1}, T_{o2}	Threshold for new calls in RAT-1 and RAT-2 respectively.
T_{1j} for $j = 1, 2$	Handoff call threshold for class-1 in RAT-j.
T_{2j} for $j = 1, 2$	Handoff call threshold for class-2 in RAT-j.
μ_1, μ_2	Mean holding time of class-1 and class-2 connections respectively.
h	Handoff rate.
z	Positive scalar step size, applied to DP1.
β, γ	Constant representing the penalty associated with new call blocking and handoff call dropping probabilities respectively.
α	Scaling factor, applied to DP1.
$P_{min_1}, \quad P_{min_2}$	The minimum price per unit time for class-1 and class-2 respectively, applied to DP1 only.
P_{max_1}, P_{max_2}	The maximum price per unit time for class-1 and class-2 respectively, applied to DP1 only.
$P^1_{j,old}, \quad P^2_{j,old} \quad (j = 1, 2)$	The current price per bbu per time for class-1 and class-2 respectively in RAT-j, applied to DP2 only.
$P^1_{j,min}, \quad P^2_{j,max} \quad (j = 1, 2)$	The minimum and maximum prices per bbu per unit time in RAT-j, applied to DP2 only.
$\lambda^n_1, \quad \lambda^n_2$	New class-1 and class-2 calls arrival rates in the group of co-located cell.
$\lambda^h_1, \quad \lambda^h_2$	Handoff class-i and class-2 calls arrival rates in the group of co-located cells.
$\varphi^1_{j,min}, \varphi^1_{j,max}$	The minimum and maximum price per bbu per unit time in RAT-j, respectively.

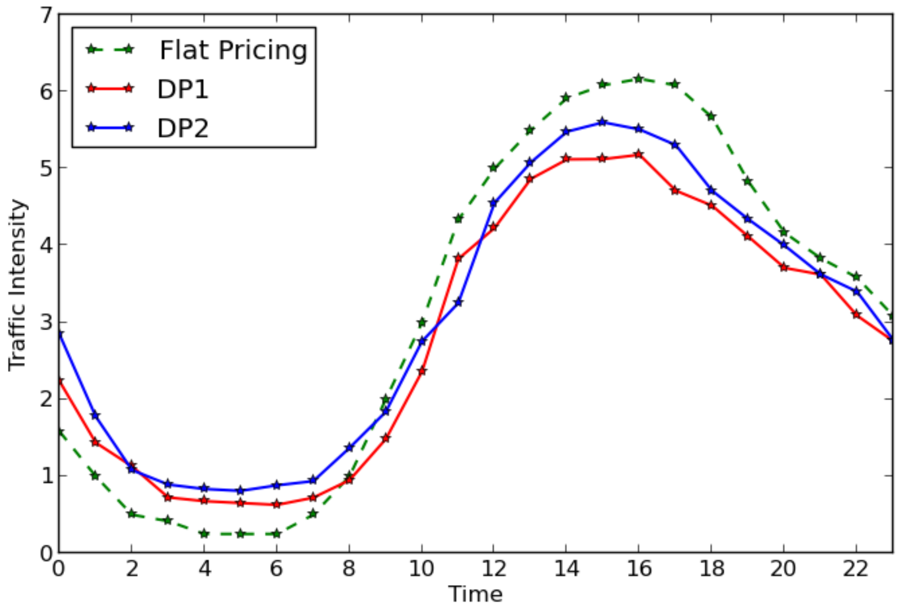

Figure 4.2: The traffic intensity by using DP1, DP2 and flat pricing schemes

of low load, which is between 0:00 am and 9:00 am, the user demand under the flat pricing scheme is lower than under the dynamic pricing schemes. With the dynamic pricing schemes, the users demand increases, however, during the congestion period, between 10:00 am and 8:00 pm, the users' demand under DP1 and DP2 decreases while flat pricing is at its highest level. The traffic demand is more constant under the two dynamic pricing schemes. DP1 and DP2 allow a balance between the off peak period of the day and the peak hours of the day. Between 9:00 pm and 11:00 pm, the user's demand under DP1 and DP2 is lower than under flat pricing.

The dynamic pricing schemes provide incentives during low load conditions to encourage users to make calls and during high load conditions, they provide incentives to discourage users from making calls.

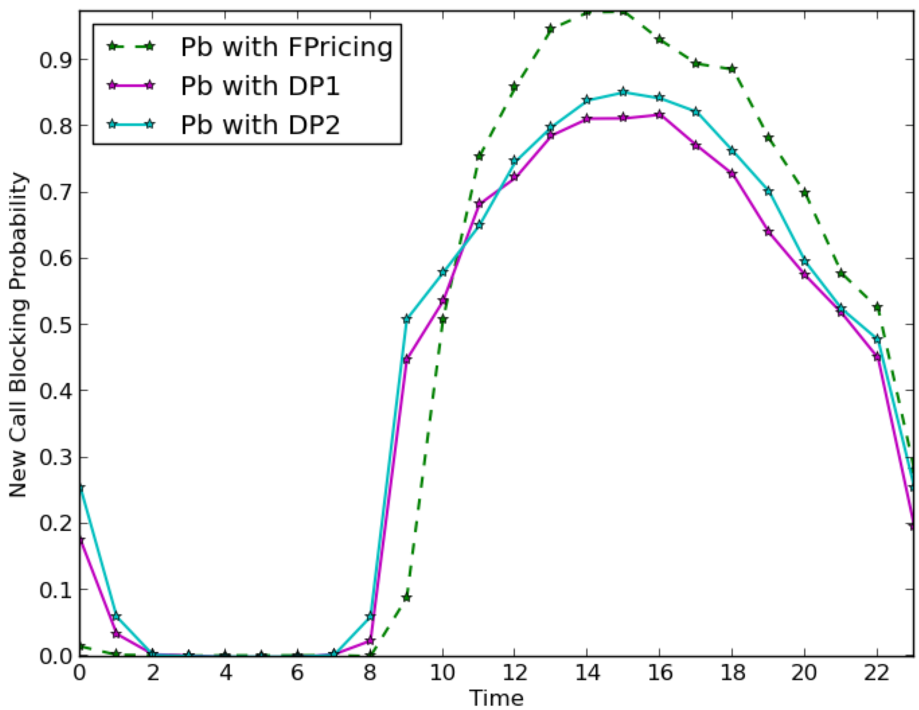

Figure 4.3: New calls blocking probability with DP1, DP2 and flat pricing

4.5.1 New calls blocking probability with the DP1, DP2 and flat pricing

Figure 4.3 illustrates the blocking probability of DP1 and DP2, where the figure shows that the blocking probability with the flat pricing scheme is higher than the blocking probability with DP1 and DP2. During the peak hours of the day, the blocking probability with DP1 is lower than the blocking probability with DP2 and flat pricing. The overall blocking probability with flat pricing is below 0.98 while the overall blocking probability with DP1 and DP2 are below 0.82 and 0.85 respectively. Therefore, the dynamic pricing schemes perform better than the blocking probability with the flat pricing.

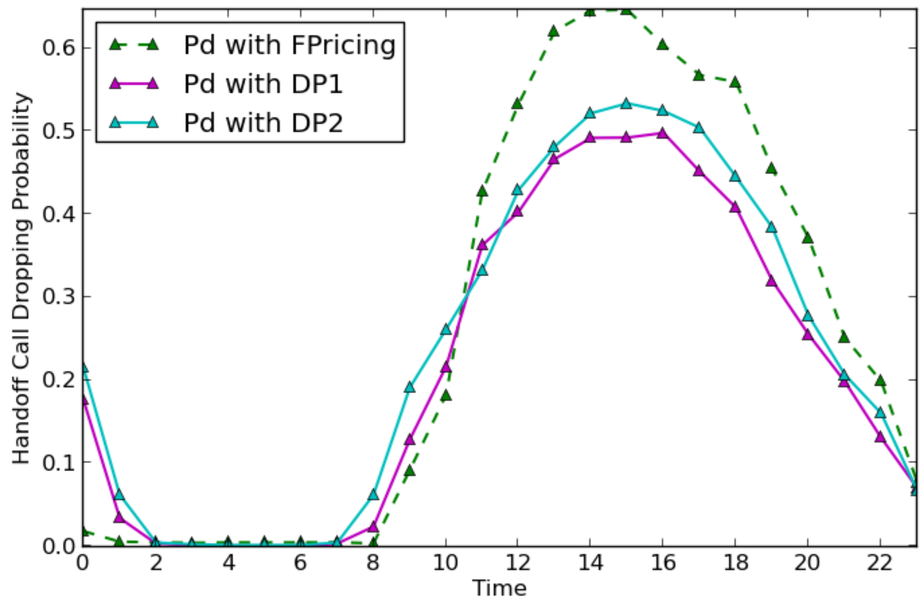

Figure 4.4: Handoff call dropping probability with the DP1, DP2 and flat pricing

4.5.2 Handoff calls dropping probability with the DP1, DP2 and flat pricing

Figure 4.4 shows the performance of the handoff calls dropping probability under the DP1, DP2 and flat pricing schemes. It is observed that during the peak hours of the day, between 10:00 am and 08:00 pm, the dropping probability with the flat pricing scheme is higher than the dropping probability with DP1 and DP2. The handoff call dropping probability is lower than the new calls blocking probability because of the bandwidth reservation policy applied for handoff calls, more bandwidths are given to aggregate only handoff calls compared to new calls as specified previously in section 3.3. The overall dropping probability under DP1 and DP2 are less than 0.50 and 0.53 respectively while the overall dropping probability under the flat pricing scheme is below 0.65. The dynamic pricing schemes perform better than the flat pricing scheme for handoff calls.

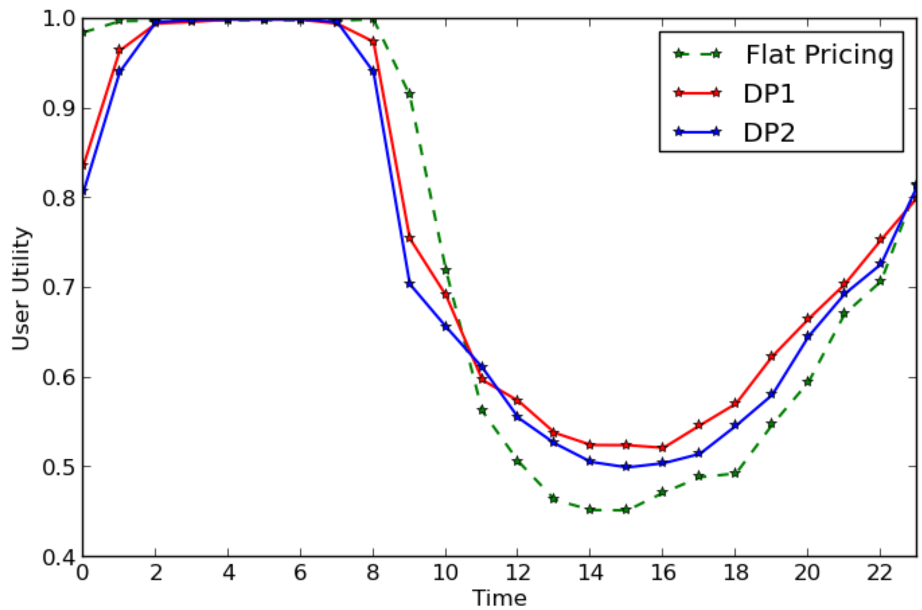

Figure 4.5: The user utility with the DP1, DP2 and flat pricing

4.5.3 User utility with the DP1, DP2 and flat pricing

User utility is evaluated all through the 24 hours of the day as illustrated in Figure 4.5. The result obtained shows that during the off peak hours of the day, the user utility under flat pricing, DP1 and DP2 are very similar. However, there is some difference that is observed between 10:00 am and 8:00 pm, the user utility under the flat pricing scheme is lower than what obtains under DP1 and DP2. During the peak hours of the day, at exactly 10:00 am, the DP1 is a little bit lower than the DP2. However, between 11:00 am and 8:00 pm, DP1 becomes higher than DP2. The average user utilities in DP1 and DP2 obtained are 0.76 and 0.75 respectively, while, the flat pricing scheme's user utility is 0.72. The average user utility under flat pricing is lower than that obtained from the dynamic pricing schemes during the congestion period. Therefore, DP1 and DP2, both guarantee a high level of satisfaction to users compared to the flat pricing scheme.

4.6 Blocking and dropping probabilities with DP1 and SCJCAC algorithm

The blocking and dropping probabilities are evaluated over time according to the increasing arrival rate of calls and the arrival rate of calls during the peak hours of the day. In this study, the DP1 and the SCJCAC algorithm, henceforth referred to as the DP1-SCJCAC algorithm have been used to evaluate the blocking and dropping probabilities because DP1 provides a better level of satisfaction to users compared to DP2 in the simulation study.

4.6.1 Blocking and dropping probabilities according to the increasing arrival rate of calls

The blocking and dropping probabilities are calculated by considering the increasing arrival rate of calls. As specified previously, voice and data calls are the classes of services considered while GPRS and UMTS are the RATs considered in HWNs. When the arrival rate of calls increase into HWN, the blocking and dropping probabilities also increase simultaneously with the SCJCAC algorithm.

4.6.1.1 New calls blocking probability

Figure 4.6 shows the call blocking probability with the SCJCAC algorithm when the arrival rate is increasing. Figure 4.6.a shows the performance of the SCJCAC algorithm for voice calls. The blocking probability is lower with the SCJCAC algorithm than the blocking probability without the SCJCAC algorithm. Figure 4.6.b shows that the blocking probability of data calls with the SCJCAC algorithm is lower than the blocking probability without the SCJCAC algorithm. Figure 4.6.c shows the blocking probability of both calls (voice and data), observation shows that the blocking probability of both calls with the SCJCAC algorithm is still lower that the blocking probability of both calls without the SCJCAC algorithm.

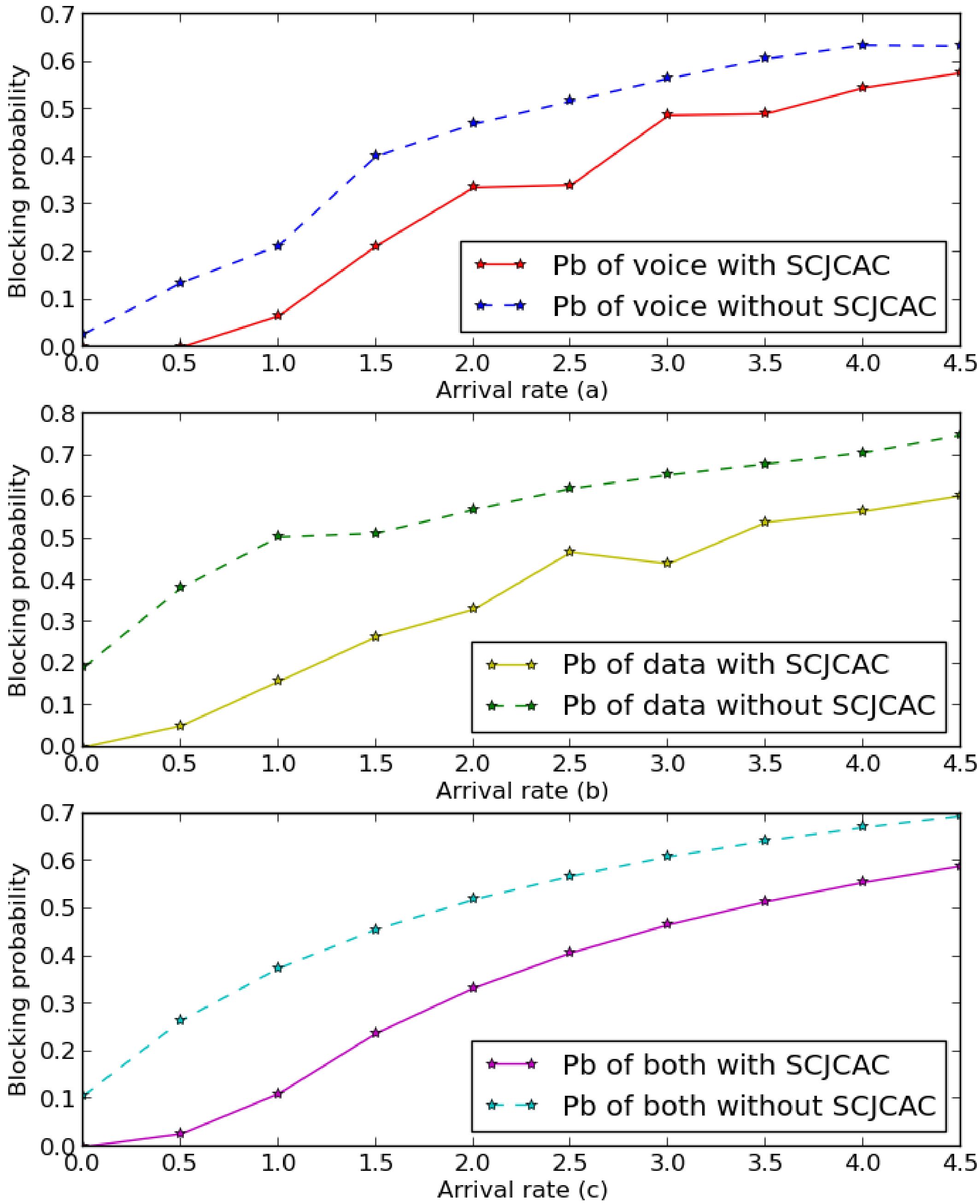

Figure 4.6: New calls blocking probability with the SCJCAC algorithm

4.6.1.2 Handoff calls dropping probability

Figure 4.7 shows the handoff call dropping probability with the SCJCAC algorithm. Figure 4.7.a illustrates that the handoff dropping probability of voice calls with the SCJCAC algorithm is lower than the dropping probability without the SCJCAC algorithm. Figure 4.7.b illustrates that the SCJCAC algorithm performs well such that the handoff dropping probability of data calls with SCJCAC algorithm is lower than the handoff dropping probability without the SCJCAC algorithm. Figure 4.7.c shows the dropping probability of both calls (voice and data). The observation shows that the dropping probability of both calls with the SCJCAC algorithm is still lower than the dropping probability without the SCJCAC algorithm.

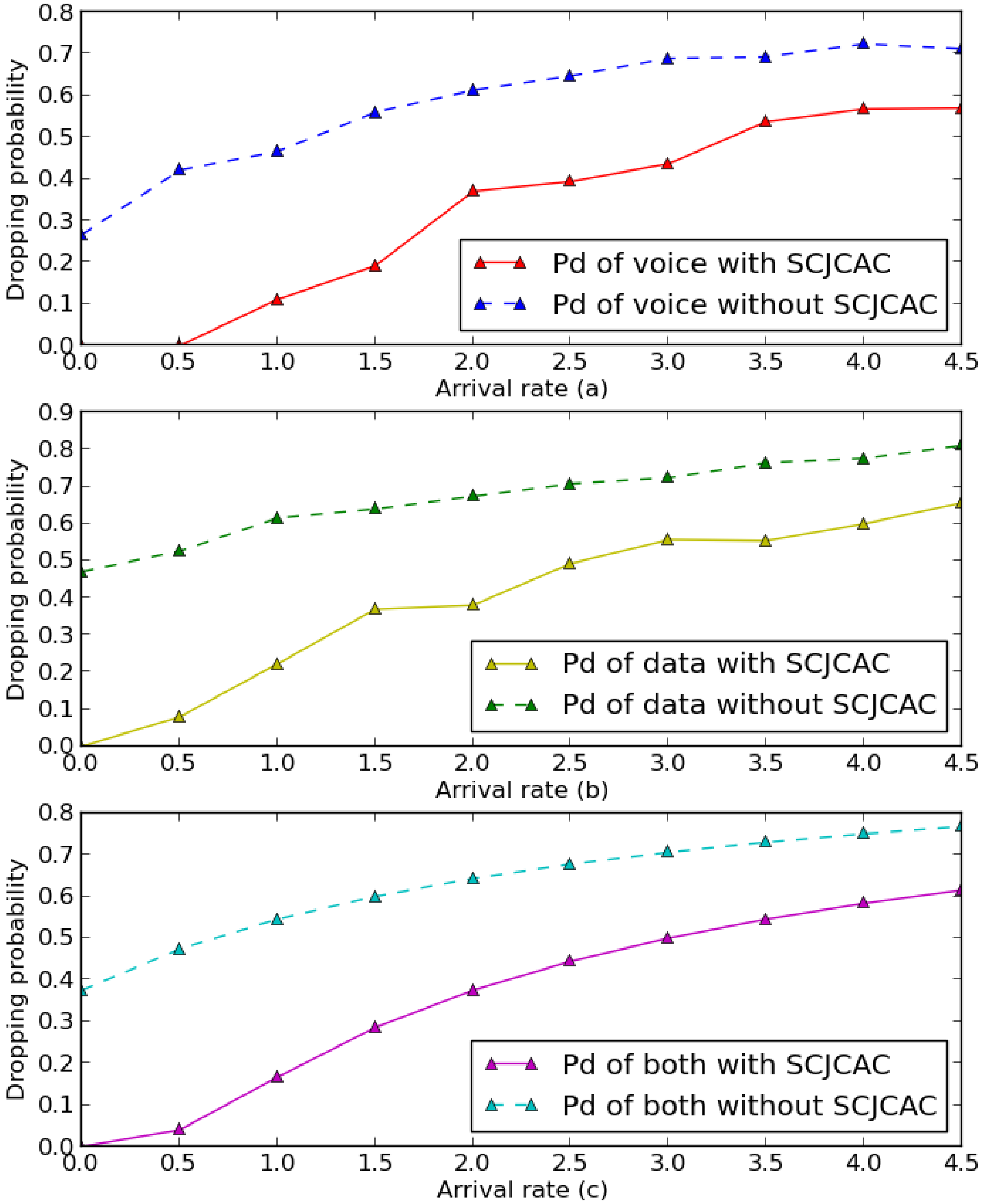

Figure 4.7: Handoff calls dropping probability with the SCJCAC algorithms

4.6.2 Blocking and dropping probabilities during the peak hours of the day

The DP1-SCJCAC algorithm has been used to evaluate the blocking/dropping probabilities.

4.6.2.1 New calls blocking probability

Figure 4.8 shows the blocking probability of new voice calls during the peak hours of the day admitted into HWNs. This figure shows that between 00:00 am and 10:00 am, the blocking probability of voice calls, with or without the DP1-SCJCAC algorithm is low and, during the period between 10:00 am and 08:00 pm, the both blocking probabilities increase.

However, the blocking probability under the DP1-SCJCAC algorithm is lower than the blocking probability without the DP1-SCJCAC algorithm. The overall blocking probability with the DP1-SCJCAC algorithm is below 0.65 while the overall blocking probability without the DP1-SCJCAC algorithm is below 0.82, which shows that the SCJCAC algorithm performs better.

Figure 4.9 shows the performance of both blocking probabilities for data calls, with and without the DP1-SCJCAC algorithm. The observation made shows that between 00:00 am and 8:00 am, both blocking probabilities are very low, in some case, less than 0.50, and this increases between 9:00 am and 10:00 am. During the peak hour of the day, the blocking probability with the DP1-SCJCAC algorithm is lower than the blocking probability without the DP1-SCJCAC algorithm. The overall blocking probability with the DP1-SCJCAC algorithm is below 0.73 and is below 0.86 for the blocking probability without the DP1-SCJCAC algorithm.

Figure 4.10 presents an evaluation of the blocking probability of both voice and data calls, which shows that the blocking probability with the DP1-SCJCAC algorithm performs better and is lower than the blocking probability without the DP1-SCJCAC algorithm. Moreover, the overall blocking probability of both calls under the DP1-SCJCAC algorithm is below 0.69 while the overall blocking probability without the DP1-SCJCAC algorithm is below 0.84. This

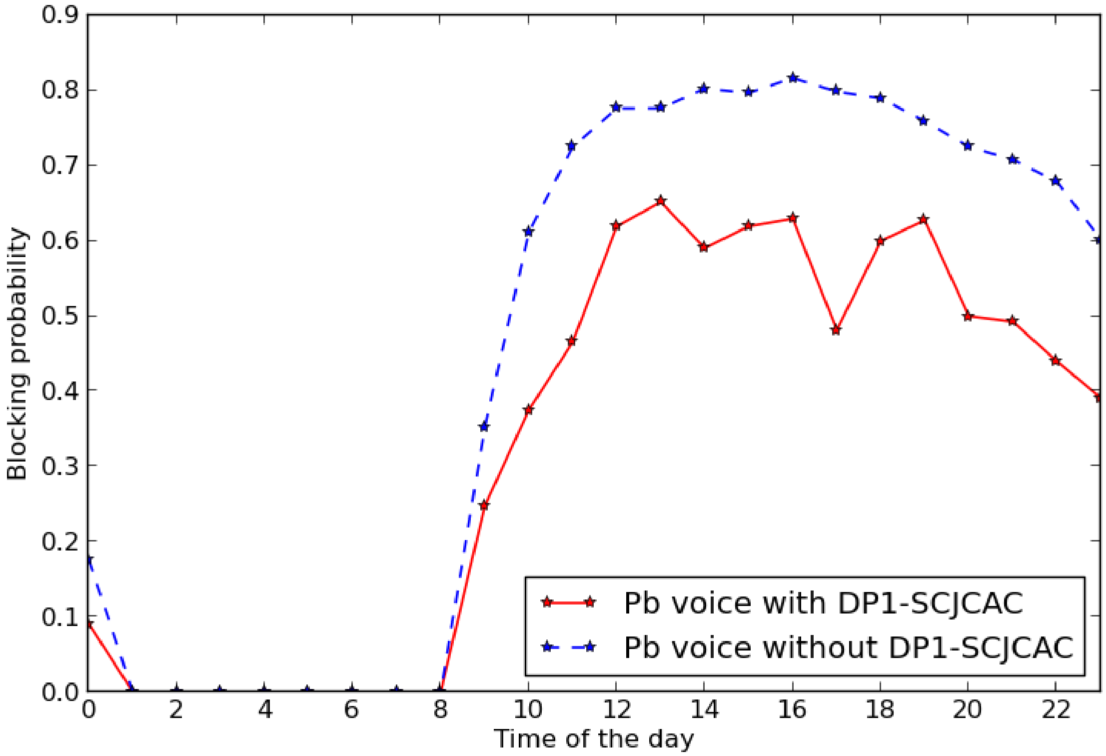

Figure 4.8: Blocking probability with DP1-SCJCAC algorithms for voice calls

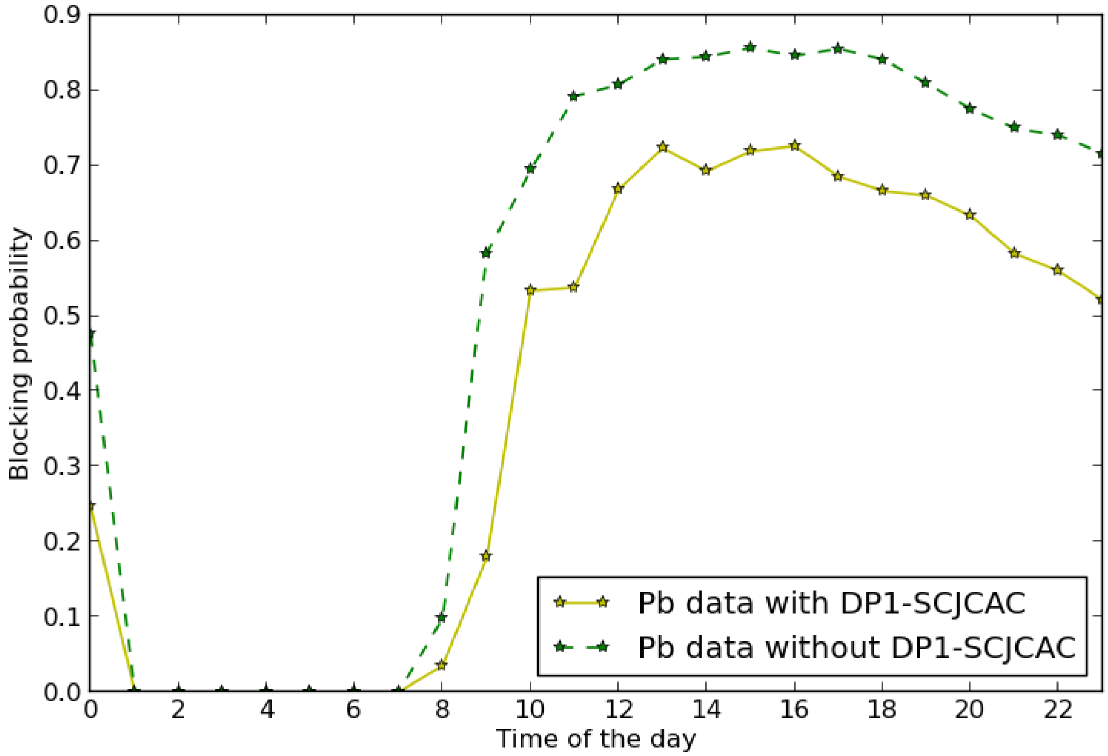

Figure 4.9: Blocking probability with the DP1-SCJCAC algorithms for data calls

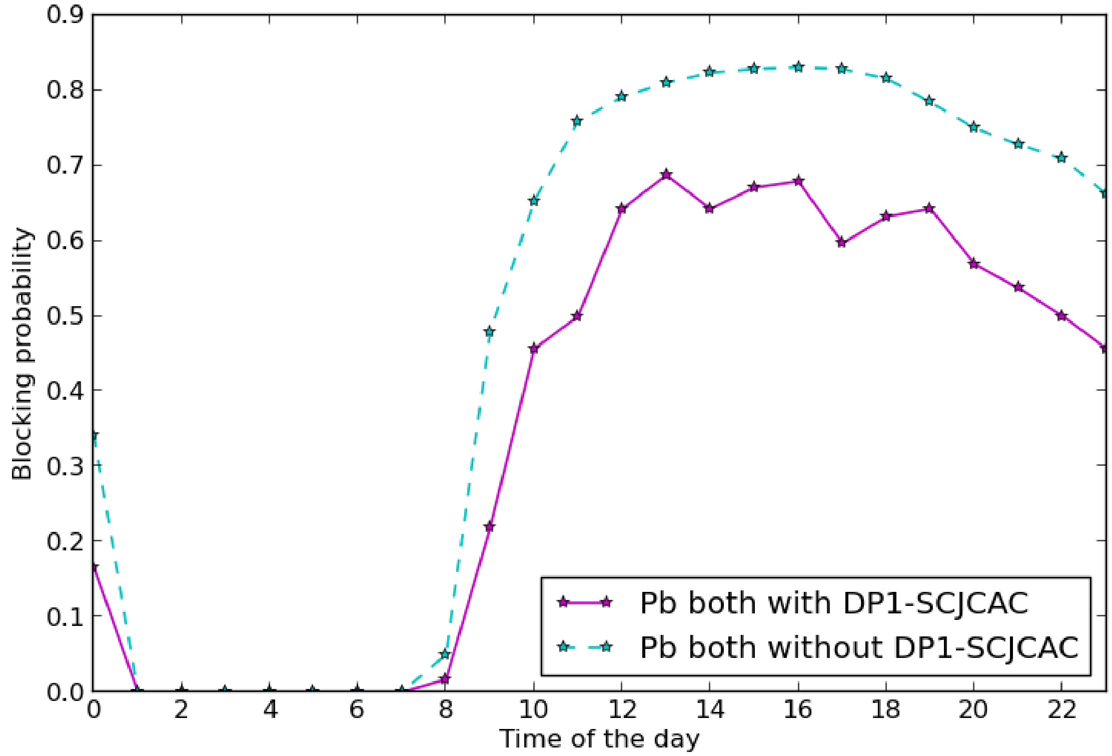

Figure 4.10: Blocking probability with the DP1-SCJCAC algorithms for both calls

result obtained shows performance of the DP1-SCJCAC algorithm.

4.6.2.2 Handoff calls dropping probability

The handoff calls have a certain priority over new calls such that a certain amount of bandwidth are exclusively reserved to handoff calls in order to keep the dropping probability low.

Figure 4.11 illustrates the handoff voice calls dropping probability. Between 00:00 am and 09:00 am, the dropping probability is very low for both schemes and it increases around 10:00 am. During the peak hour of the day, between 10:00 am and 08:00 pm, the dropping probability with the DP1-SCJCAC algorithm is lower than the dropping probability without the DP1-SCJCAC algorithm. The overall handoff call dropping probability with the DP1-SCJCAC algorithm

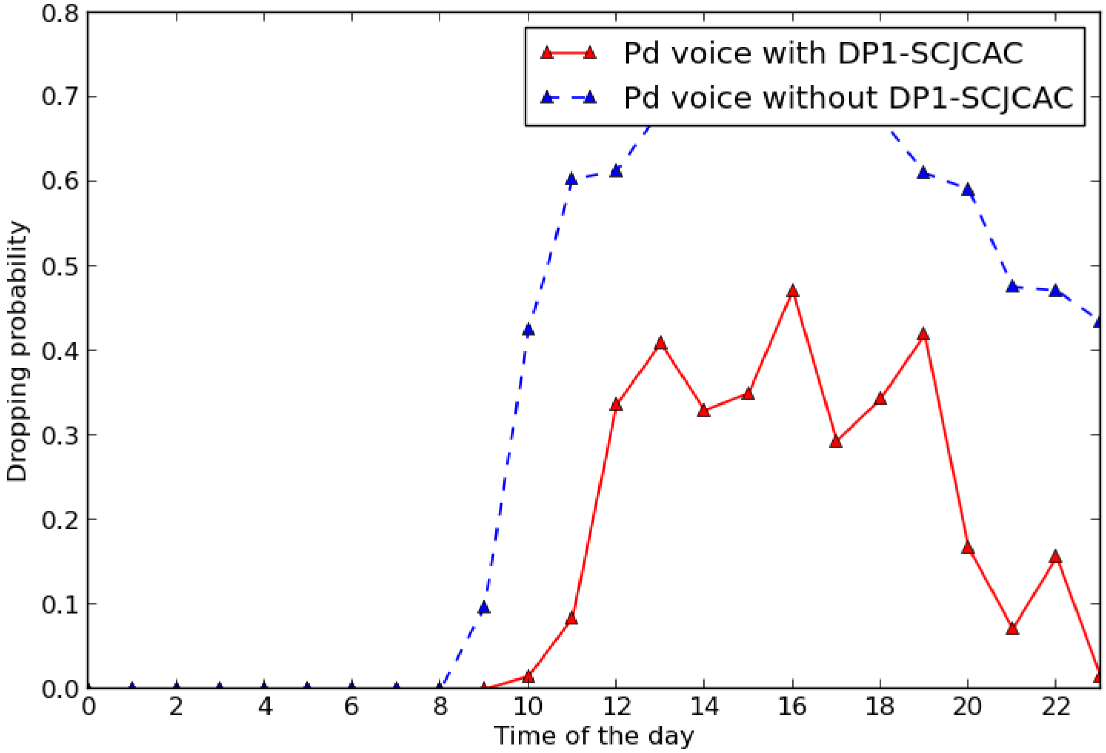

Figure 4.11: Dropping probability with the DP1-SCJCAC algorithm for voice calls

is below 0.47 while the overall handoff call dropping probability without the DP1-SCJCAC algorithm is below 0.72.

Figure 4.12 illustrates the handoff data call dropping probability. The dropping probability of both schemes are very low between 0:00 am and 10:00 am. During the peak hours of the day, between 10:00 am and 08:00 pm, the handoff dropping probability under the DP1 and SCJCAC algorithm is lower than the handoff dropping probability without the DP1-SCJCAC algorithm. The overall dropping probability without the DP1-SCJCAC algorithm is below 0.74 while the overall dropping probability with the DP1-SCJCAC algorithm is below the 0.58.

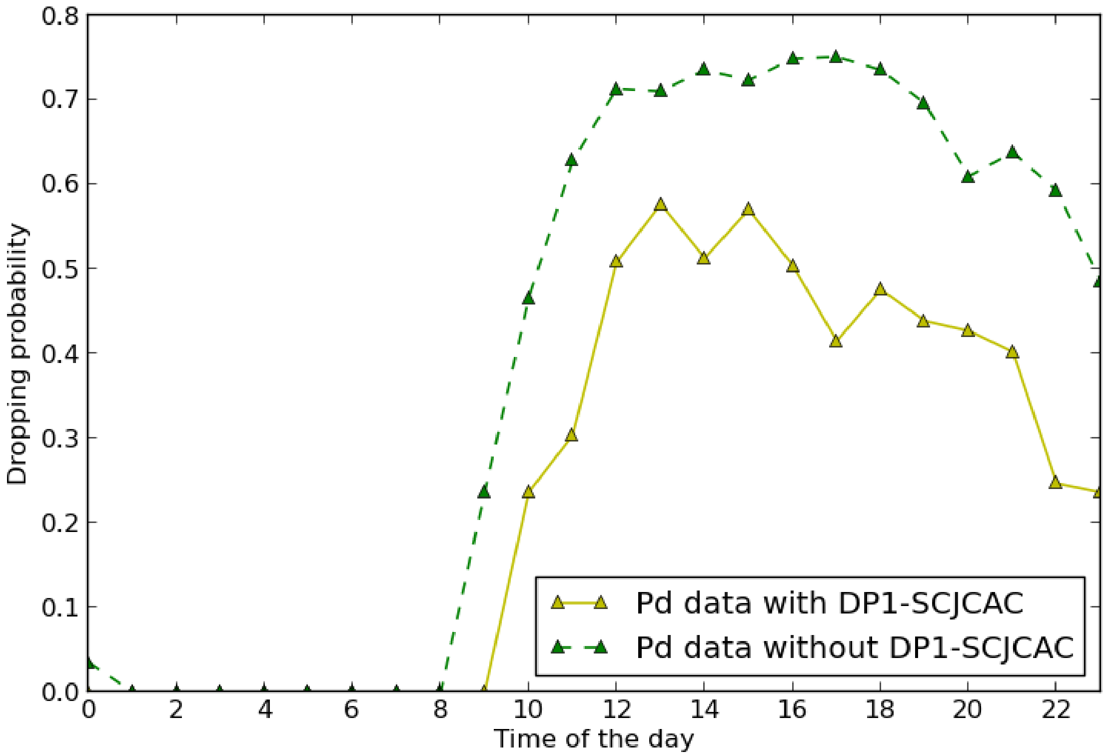

Figure 4.12: Dropping probability with the DP1-SCJCAC algorithm for data calls

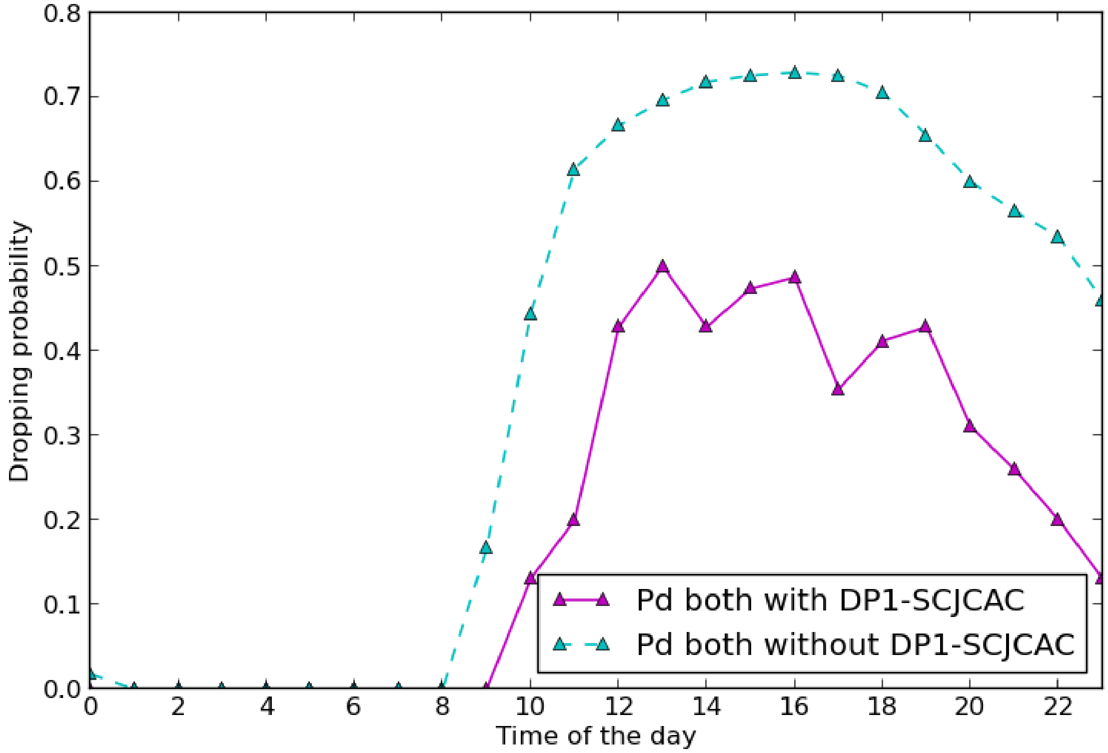

Figure 4.13: Dropping probability with the DP1-SCJCAC algorithms for both calls

Figure 4.13 shows the performance of the handoff call dropping probability for both calls (voice and data). It is observed that the dropping probability without the DP1-SCJCAC algorithm is higher than the dropping probability with the DP1-SCJCAC algorithm and the overall is below 0.73 while the overall dropping probability with the DP1-SCJCAC algorithm is below 0.49.

4.7 User utility with DP1-SCJCAC Algorithm

Figure 4.14 shows the user utility for voice calls. During the off peak hours of the day, the users are fully satisfied with the two schemes, however during the peak hours of the day, the user utility under the DP1-SCJCAC algorithm is higher than the user utility with flat pricing. The

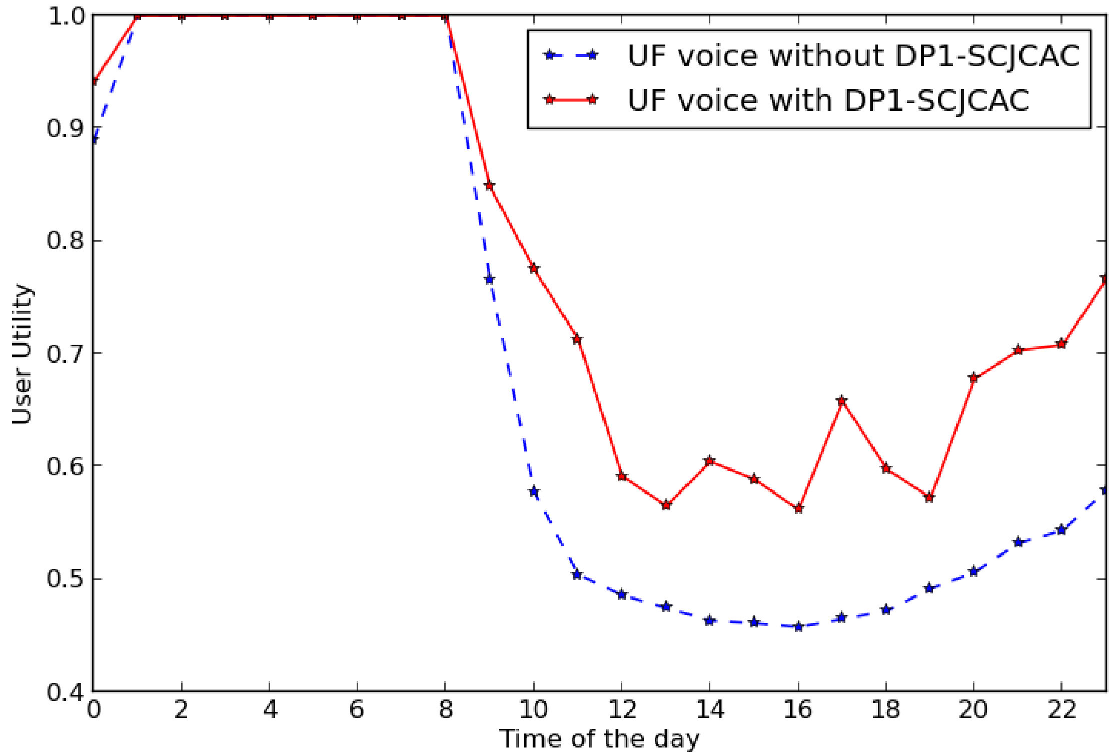

Figure 4.14: User utility with the DP1-SCJCAC algorithm for voice calls

average user utility under the DP1-SCJCAC algorithm is 0.77 while the average user utility with flat pricing is 0.72.

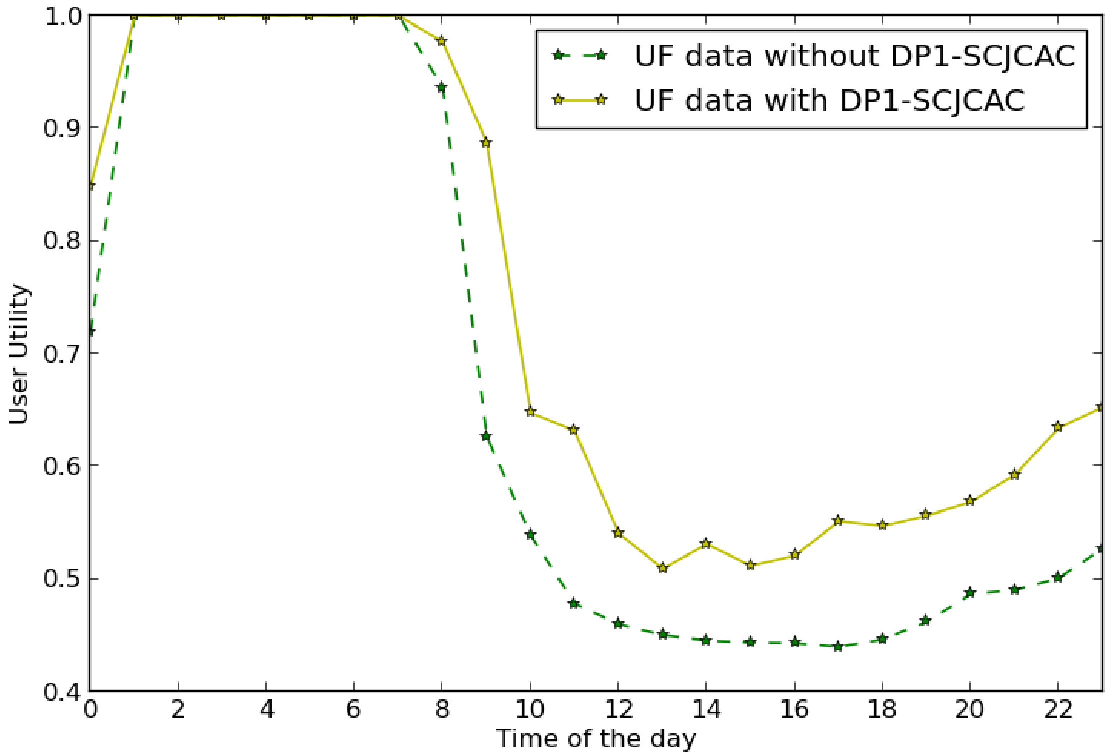

Figure 4.15: User utility with the DP1-SCJCAC algorithm for data calls

Figure 4.15 presents the evaluation of user utility for data calls. The result obtained is similar to that presented in Figure 4.14. However the average user utility under the DP1-SCJCAC algorithm for data calls is 0.73 while the average user utility with flat pricing is 0.68.

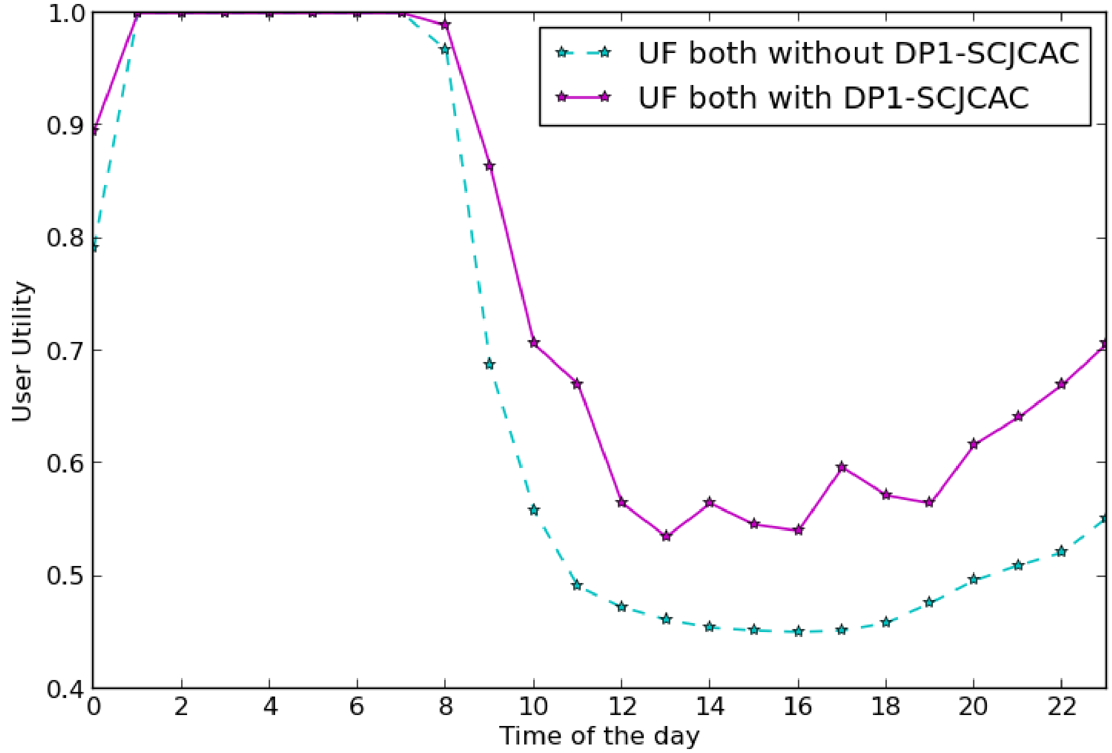

Figure 4.16: Users utility with the DP1-SCJCAC for both calls

Figure 4.16 illustrates the user utility of both calls. During the peak hours of the day, the level of satisfaction derived from both calls under the DP1-SCJCAC algorithm is higher than the user utility with flat pricing. The average user utility with the DP1-SCJCAC algorithm is 0.77 while the average user utility with flat pricing is 0.70.

The following Table 4.2 contain the results obtained in the above graphic simulations for the user' utility results under the DP1, DP2 and DP1-SCJCAC algorithm. It is observed that DP1 and DP1-SCJCAC give better results and satisfaction to users than DP2 during the off hours and the peak hours as well. However, DP1-SCJCAC performs better than DP1. During the peak period, DP1-SCJCAC gives a better level of satisfaction and sometimes DP1 perform better than DP1-SCJCAC.

Table 4.2: Results obtained for users' utility under the DP1, DP2 and DP1-SCJCAC

Users utility			
Time	DP1-SCJCAC	DP1	DP2
0	0.8948393168143698	0.8369027155052998	0.807512436900995
1	1.0	0.9649724523401091	0.9411472544528364
2	1.0	1.0	1.0
3	1.0	1.0	1.0
4	1.0	1.0	1.0
5	1.0	1.0	1.0
6	1.0	1.0	1.0
7	1.0	1.0	1.0
8	0.9889503892939223	0.9749724523401091	0.9411472544528364
9	0.8685877175391203	0.7555690256193075	0.7047386598519769
10	0.7062216866978064	0.6919648165919492	0.657032965314942
11	0.6703200460356393	0.59781225597642	0.6117617943951099
12	0.5681533686943423	0.5742424066971189	0.5553436085989256
13	0.5603887278885606	0.5387265875683234	0.5269952477352167
14	0.5544778308826918	0.5252096483127473	0.5062965657309758
15	0.5490628659528098	0.5250203308293309	0.5002448818576439
16	0.5495601221613163	0.5220849986238988	0.5048775418107689
17	0.6071566404338008	0.5470203308293308	0.515244881857644
18	0.5917575048579576	0.5713486030919289	0.5467355924484067
19	0.6471448143486154	0.6240149971667357	0.5811714736649801
20	0.6634094235942375	0.6657566481464504	0.6462757075536956
21	0.6651918800205268	0.7045410130711496	0.693877553828141
22	0.6971215769343144	0.7539454093700113	0.7269174817947434
23	0.7157979111387981	0.8011942119122022	0.814168961709861

4.8 Summary

This chapter has evaluated and compared two recent dynamic pricing schemes, where level of satisfaction for each scheme is obtained via the simulation and the blocking/dropping probabilities for the two dynamic pricing schemes have been compared with the flat pricing scheme. In addition, the SCJCAC algorithm proposed in literature, as presented in chapter 3, has been used with DP1 and evaluated in simulation where two different RATs and two different classes of services have been considered. The result obtained has been compared with a case where the JCAC algorithm and the flat pricing scheme are absent. The blocking/dropping probabilities have been evaluated in a situation when the arrival rate of calls is increasing and there is congestion during the peak hours of the day, the result has been compared with that obtained from a flat pricing scheme. Moreover, user utility under both the DP1 and DP2, and the SCJCAC algorithm has been evaluated and compared with user utility under the flat pricing. The result obtained reveals the high level of satisfaction obtained from the SCJCAC algorithm scheme compared to the flat pricing scheme. Therefore, the two dynamic pricing schemes and the SCJCAC algorithm perform better than the flat pricing scheme.

Chapter 5

Conclusion and future research

5.1 Conclusion

This research thesis has presented two recent dynamic pricing schemes and a flexible SCJCAC algorithm to reduce congestion during peak periods. The two dynamic pricing schemes have been investigated, their traffic distribution during the peak period have been evaluated in simulation. The result obtained for user utility shows that DP1 performs better than DP2. The level of satisfaction under DP1 is higher than DP2, considering the fact that DP1 uses a discount policy with a scaling factor in determining a new price. The dynamic pricing schemes have been incorporated with a load-based JCAC algorithm to control congestion in HWNs. The call blocking/dropping probabilities are lower under both dynamic pricing schemes than under the flat pricing scheme. Moreover, the level of satisfaction is higher under the two dynamic pricing schemes than under the flat pricing scheme. The result obtained revealed that the dynamic pricing schemes are techniques that have reduced the blocking and dropping probabilities that occur during the peak hours of the day into HWNs.

A flexible SCJCAC algorithm has been proposed and modelled using the Markov decision process, and this was used with the DP1 to accommodate the various classes of services into the appropriate RAT, where the radio resource allocation of the RATs has been managed efficiently into HWNs. Two classes of services and two RATs have been considered. The performance of the flexible SCJCAC algorithm has been evaluated by determining the new call blocking/ handoff call dropping probabilities and the user' utility functions.

Besides, when the arrival rate increases in HWNs, the call blocking or dropping probabilities increase as well. However, the call blocking/dropping probabilities under the SCJCAC algorithm is lower than the blocking/dropping probabilities without the JCAC algorithm. The evaluation for blocking/dropping probabilities has been done for voice, data and both classes of service into two types of RATs; GPRS and UMTS. The results obtained are compared with blocking/dropping probabilities without dynamic pricing and SCJCAC algorithm. The blocking/dropping probabilities under the DP1-SCJCAC algorithm are lower than with flat pricing. The average user utility under the DP1 and SCJCAC algorithm is higher than the average user utility with the flat pricing and without the SCJCAC algorithm for voice, data and both classes of services.

Thus, this research thesis has shown that two recent dynamic pricing schemes presented, performed better than the flat pricing scheme. In addition, the SCJCAC algorithm with DP1 gave a good results for reducing and controlling the congestion into HWN during the peak hours of the day.

5.2 Future research

The RATs considered in HWNs are assumed to fully overlap, this means the RATs offer full coverage to users. Future research could consider RATs which partially overlap and those that do not overlap. The SCJCAC algorithm can consider the possibility of different RATs interworking such as WLAN and UMTS, etc. The flexible SCJCAC algorithm could be incorporated with the DP2 or with other dynamic pricing schemes, to control congestion in HWNs. Though, the JCAC algorithm used in this thesis is a service class-based incorporated with DP1, future research could consider the possibility of the DP1 being integrated with other JCAC algorithms such as service cost-based, random based, path loss-based etc. as enumerated in literature.

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