CONGESTION CONTROL IN MULTI-SERVICE HETEROGENEOUS WIRELESS NETWORKS USING DYNAMIC PRICING

Samson Oluwashina, Orimolade

This dissertation is submitted in partial fulfillment of the academic requirements
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As the candidate's supervisor, I have approved this dissertation for submission.

Name: Dr. Olabisi Falowo

Signed: ______________________

Date: ________________________

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DEDICATION

I dedicate this work to the Lover of my soul, and to my glorious family ahead, who will live according to the precepts of God.

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I give all glory to God for HIS guidance and strength throughout my research period, it was a challenging period of my life, but God saw me through it all.

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ABSTRACT

Network congestion is still a major problem in multi-serviced heterogeneous wireless networks (HWNs), despite the installation of more macro and micro base stations and the deployment of more efficient Radio Access Technologies (RATs) such as 3G and LTE. Congestion is caused by the increasing number of subscribers, ground-breaking technologies in the smart-mobile world and advent of new user-friendly applications. As users utilize the resource-constrained network, they crave to increase their Quality of Service (QoS) and monetary utility. This is a challenge for Service Providers (SPs) because they must ensure an effective and efficient delivery of services while reducing operational cost and increasing profit. On the other hand, the revenue generated by an operator depends on the number of successful calls made by users and this translates to higher profits for the operator. In an attempt to solve the problem of congestion and efficient utilization of radio resources for revenue enhancement, an economic approach that integrates a collaborative pricing scheme to the conventional call admission control (CAC) will be viable.

When the demand for radio resources becomes excessive, the provisioned capacity of the network reaches the congestion stage, which may lead to high level of new call blocking and handoff call dropping probability figures that are undesirable. On the other hand, when there is a low demand for radio resources, the capacity is underutilized and this result to wastage of resources. However, operators do not desire underutilization as well as the congestion stages of the network resources. These extreme levels of utilization can be avoided by developing an intelligent dynamic pricing scheme, which is named the collaborative dynamic pricing scheme.

Service providers, (or operators) employ pricing schemes to help provide desired QoS to subscribers and to maintain profitability among competitors. An economically efficient pricing scheme, which will seamlessly integrate users' preferences as well as service providers' preferences, is therefore needed. Else, pricing schemes can be viewed as promoting social unfairness in the dynamically priced network. However, earlier investigations have shown that the existing dynamic pricing schemes do not consider the users' willingness to pay (WTP) before the price of services is determined. WTP is the amount a user is willing to pay based on the

worth attached to the service requested. There are different WTP levels for different subscribers due to the differences in the value attached to the services requested and demographics.

This research has addressed congestion control in the heterogeneous wireless network (HWN) by developing a dynamic pricing scheme that efficiently incentivises users to utilize radio resources. The proposed Collaborative Dynamic Pricing Scheme (CDPS), which identifies the users and operators' preference in determining the price of services, uses an intelligent approach for controlling congestion and enhancing both the users' and operators' utility. Thus, the CDPS addresses the congestion problem by firstly obtaining the users WTP from users' historical response to price changes and incorporating the WTP factor to evaluate the service price. Secondly, it uses a reinforcement learning technique to illustrate how a price policy can be obtained for the enhancement of both users and operators' utility, as total utility reward obtained increases towards a defined 'goal state'.

The performance of the proposed CDPS is evaluated using MATLAB simulation tool, and the simulations are analysed for different demand level scenarios. The relevant performance metrics considered are call blocking and call dropping probabilities, network utilization and, users and operators' utility. Simulation results show that the proposed CDPS reduced congestion in HWNs, and enhanced users' and operator's utility by efficiently incentivizing users to make call requests at appropriate time.

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LIST OF ACRONYMS

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AHP	Analytical Hierarchy Process
BAK	Bill And Keep
BBU	Basic Bandwidth Units
BSS	Billing Support Systems
CAC	Call Admission Control
CoS	Class of Service
CPP	Call Party Pays
CRM	Customer Relationship Management
CRRM	Common Radio Resource Management
DVB-H	Digital Video Broadcasting-Handheld
EDGE	Enhanced Data Rate for GSM Evolution
EPC	Evolved Packet Core
EV-DO	Evolution Data Optimized
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GRA	Grey Relational Analysis
HD	High Definition
HQ	High Quality
HSPA	High Speed Packet Access
HWN	Heterogeneous Wireless Networks
ICT	Information and communication Technologies
IMS	Internet Protocol Multimedia Services
IP	Internet Protocol
IT	Information Technology
ITU	International Telecommunication Union

LTE	Long Term Evolution
MADM	Multiple Decision Making
MATLAB	Matrix Laboratory
MDP	Markov Decision Process
MVNOs	Mobile Virtual Network Operators
NGWN	Next Generation Wireless Networks
NS2	Network Simulator 2
NS3	Network Simulator 3
OPNET	Optimized Network Engineering Tools
OSS	Operations Support Systems
PCRF	Policy and Charging Rules Function
PDF	Policy Decision Function
PSM	Price Sensitivity Measure
PSF	Price Sensitivity Function
P2P	Point to Point
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RL	Reinforcement Learning
RPP	Receiving Party Pays
RRM	Radio Resource Management
SLA	Service Level Agreement
SON	Self Organizing Networks
SPs	Service Providers
UMTS	Universal Mobile Telecommunication System
VIP	Very Important People
VoLTE	Voice over Long Term Evolution
VPSM	Van-Westendorp Price Sensitivity Meter
W-CDMA	Wide Band Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

WLAN	Wireless Local Area Network
WSPs	Wireless Service Providers
WTP	Willingness To Pay

Chapter 1

1 INTRODUCTION

The telecommunications industry has evolved over the years with astonishing growth in the market, due to developments and technological advancements, it has also coped with the unprecedented increase in the number of subscribers. The continuous growth in mobile broadband demand from the International Telecommunication Union (ITU) world telecommunication and Information and Communication Technology (ICT) indicators database released in 2013, shows that mobile broadband subscriptions grew from 268 million in 2007 to 2.1 billion in 2013, this translates to a 40% increase in annual growth [1]. An unprecedented increase was recorded in developing countries, which more than doubled between the years, 2011 and 2013, from 427 million to 1.16 billion and exceeded those in developed world. Africa being the region with the highest growth rates over the past three years, witnessed an increase in mobile broadband penetration from 2% in 2010 to 11% in 2013. The figures keep surging with higher demand for diverse services on the network. The driving key-words for the evolving paradigm of wireless communication (called the Next Generation Wireless Networks (NGWN)) are optimization, harmonization and integration of networks and services [2].

With this rapid growth rate, the telecommunication industries continue to introduce innovative ways of handling this growth by providing more efficient technological mechanisms. The number of subscribers craving for high bandwidth consuming services has led to the innovation of more efficient telecommunication paradigm. The possibility of realizing the 'connected everywhere, anytime, anyhow' philosophy which is aimed at meeting subscribers demand will require economically efficient business models, intelligent technological prowess and innovative implementations.

The evolution of the telecommunication core and access network is motivated by the need to meet the demand of the market. Users are becoming more technologically driven with a rising demand for more efficient and satisfying ways of interacting with the network. This evolutional trend coined the phrase 'next generation', a phrase used to describe the features or expectations of the capabilities of envisioned telecommunication network. As evolution unfolds, the telecommunication industries ensure that they meet up with users demand and provide the state of the art technology, which improves the overall users' Quality of Experience (QoE). The evolution in network technology is such that the recently developed RAT aims at mitigating the shortcoming of the previously deployed one. As a result, capacity is enhanced in the telecommunication network. For example, the Internet Protocol (IP) creates prospects for using packet switching for voice, data and video on the 4G technology specifications, which is an enhancement on the previous lower generations of network, such as the 2G, 3G and 3.5G RATs. The telecommunication paradigm keeps evolving, with greater sophistication envisaged. The evolution proceeded from the fixed mobile line, which is circuit switched, to the IP based next generation networks and then the future internet of things called the post-IP paradigm [3], which have received much attention recently.

The concept of the Heterogeneous Wireless Networks (HWN) was developed to improve efficiency, by integrating the capability of RATs from different generations. Heterogeneous wireless network consists of multiple RATs coexisting in the same geographical location, and supporting multiple services (calls) such as voice, video and data. Network heterogeneity introduced a new paradigm to the network orientation and architecture. In cooperative heterogeneous wireless networks (HWN), radio resources of multiple RATs are jointly managed for enhanced quality of service (QoS) provisioning and improved radio resource utilization. It is assumed that the resources are available in a 'pool' which is managed by the Joint Radio Resource Management (JRRM) or the Common Radio Resource Management (CRRM) schemes. The HWN creates more room for users to explore the combined capabilities of the individual RATs.

In a telecommunication network, when the demand for radio resource reaches the provisioned capacity, poor quality of service may be experienced in the network and further call requests will be rejected, which can be referred to as congestion. Congestion is still a major problem in HWN, despite the installation of more macro and micro base stations and deployment of more efficient radio access technologies such as the 3G and LTE. Congestion is due to increase in number of subscribers using the network and increase in bandwidth demand per subscriber, as more subscribers use high bandwidth-consuming services.

Over the years, the mobile network market has grown to be highly competitive. A mobile network service provider or operator needs a good marketing strategy to stay in business or risk losing customers to competitors. A service provider that ensures its subscribers have a higher degree of satisfaction than that of its competitors will always take the leading edge in the telecommunication market. Therefore, network operators are looking for means to ensure that network resources are optimally utilized, users' utility is enhanced and revenue is maximized.

1.1 Problem Statement

The increase in demand for radio resources is due to the advent of new user terminals capable of running mobile applications that consumes high bandwidth and increase in number of subscribers in the wireless networks. This increase in number of subscribers running high bandwidth consuming applications creates a major challenge in managing the provisioned capacity of the radio access technologies. When the RATs available on the telecommunication network are oversubscribed, congestion will occur in the network. Congestion leads to degrading of QoS provisioned because more users contend for the limited radio resources available.

In a bid to control the demand, available services on the network are priced dynamically. Users' sensitivity to price enables the control of usage by regulating service price as the radio resources are being utilized. However, pricing network services to limit users' demand for network access may be viewed as socially unfair by users if it is not done intelligently to consider users' response to price, thereby adversely affecting the revenue of operators. ITU indicators of 2013 show a decline in revenue even as network capacity increases. This creates a problem and motivates a revolutionary pricing scheme that will forestall decrease in operators' revenue. It is consequently important to develop pricing schemes that controls congestion and take into cognizance the enhancement of users and operators' utilities. The proposed scheme therefore mitigates this problem by ensuring prices of services are done in an efficient way.

1.2 Objective of Research

The objective of this research is to develop a collaborative mechanism for managing the network resources for the enhancement of both users and operators' utility. The network resource of interest for this research is basic bandwidth unit for different classes of service. Example of users' utility are monetary and QoS utilities, while operators' utility can be in terms of radio resource utilization and revenue. Using a dynamic economic approach, congestion in the network can be controlled by introducing an incentive in form of price adjustments, to ensure that users limit their consumption of radio resources during peak period and consume more when the network is underutilized. Network users are price sensitive. Hence pricing can be used to address congestion issues especially during the peak period. An economic approach can drastically reduce congestion problem in HWNs.

The specific objectives of this research are to:

- Develop a collaborative dynamic pricing scheme that will enhance users and operators' utilities
- Evaluate the performance of the proposed scheme in a heterogeneous wireless network
- Investigate users' sensitivity to dynamic pricing using the utility function
- Investigate the effect of the proposed scheme on congestion control

1.3 Methodology

The methodology adopted in this work is to numerically simulate the performance of the proposed collaborative dynamic pricing scheme using MATLAB tool. A Reinforcement Learning (RL) algorithm is incorporated to illustrate a reward-driven price policy that takes into cognizance users and operators' preferences for service price evaluation.

An analytical model is developed for the proposed pricing scheme in a HWN using the Markov Decision Process (MDP). The developed model has different utilization levels and associated reward. It also incorporates users' willingness to pay, which is obtained from a demand function and a table of preference that describes users and operators' utilities. Four utilization levels (states) are chosen based on network load and demand. The preference table, which gives the utility of both users and operators at different utilization levels, is formulated. The ‘goal state’ is marked on the preference table as the state that enhances the utility of both users and the operator.

The Q-Learning algorithm is introduced to illustrate the service price determination based on total utility reward. The Q-Learning uses the preference table to collaborate the users and operators’ preferences, as utilization level changes. The aim is to ensure that the users are motivated to make call requests that will drive the network to the ‘goal state’ with time, consequently controlling congestion and enhancing both users’ utility and network operators’ utility.

The performance is evaluated considering blocking and dropping probabilities, users’ utility and operators’ revenue.

1.4 Scope of Research

This research focuses on development of a collaborative dynamic pricing scheme for controlling congestion in an HWN by incorporating users’ WTP in determining optimal congestion price of network services. It uses a demand model to determine users’ arrival rate into the network as a function of price.

The demand function is somewhat limited due to the different user behavior available in the network. Some users will make any call request irrespective of the price at any time. This introduces a shortcoming to the use of demand model to determine user’s WTP. Therefore, we assume that reasonable percentage of users will make connection request or have sufficient WTP as price and network utilization changes.

Finally, in a scenario where different SPs adopt different pricing policies, there will be pricing complications. Therefore, this research only considered the performance of the proposed CDPS on the revenue of a single operator.

1.5 Research Contributions

The contributions of this work are as follows:

1. Development of a collaborative dynamic pricing scheme for controlling congestion in the HWN by obtaining an optimal price policy that will efficiently incentivise enough number of users to utilize the network resources in an effective manner.

2. Incorporation of users' willingness to pay in the collaborative dynamic pricing scheme which dynamically determines service prices in the network and thereby drive the network utilization to a goal state.

3. Investigation of users' price sensitivity to dynamic pricing using the utility function.

1.6 Peer-reviewed publication

Some of the author's contributions are contained in the following peer-reviewed publication:

Samson O. Orimolade and Olabisi Falowo, "Congestion Control in Multi-Serviced Heterogeneous Wireless Networks Using Dynamic Pricing (with Users' Willingness to Pay Incorporation)", proceedings of Southern African Telecommunications Networks and Applications Conference (SATNAC), The Boardwalk, Port Elizabeth, Eastern Cape, South Africa, 31st August - 3rd September, 2014.

1.7 Thesis Outline

The remainder of this dissertation is organized as follows:

Chapter 2 gives a general overview of Heterogeneous Wireless Networks (HWN) and radio resource management in NGWN. The features of the global vision of radio resource management are presented and the approaches to decision making in network selection are also presented. The effect of congestion in Heterogeneous wireless networks and its inherent challenges are discussed. Furthermore, existing methods of controlling congestion in HWN in the literature are reviewed. The telecommunication markets shifts, strategies and pricing schemes are equally discussed. Finally, related work on congestion control in heterogeneous wireless networks are reviewed.

Chapter 3 presents the proposed scheme analysis. The HWN model and utilization conditions are described. Approach to modelling users' willingness to pay is presented. A flowchart for the proposed dynamic pricing scheme is presented and the incorporated RAT selection algorithm is explained. The Q-learning method is modelled to suit the characteristics of the HWN. Finally, relevant performance metrics is introduced to evaluate the efficiency of the proposed scheme.

Chapter 4 gives the requirement and limitation of the evaluation framework. This chapter describes the preference table that aids the evaluation of the associated reward obtained as the price of service changes with utilization. The goal state which enhances both users' and operators' utility, as utilization and service price changes is also described. Finally, utilization state scenarios are chosen to achieve the envisaged performance of the proposed pricing scheme.

Chapter 5 presents the numerical simulation results and examples to demonstrate the efficiency of the proposed scheme. The MATLAB simulation tool is used in evaluating the scheme. The performance of the proposed pricing scheme (CDPS) is examined for congestion control and utility enhancement. The total utility reward is presented showing how price policy converges to a goal state most of the time. Lastly, results showing users and operators' utility enhancement is presented.

Chapter 6 presents the conclusion and recommendations of this research. Highlights of further works as well as limitation of the thesis are presented.

2 BACKGROUND AND LITERATURE REVIEW

The radio resources available on wireless networks require efficient utilization, which is the objective of the Radio Resource Management (RRM) schemes. The advent of Heterogeneous wireless networks (HWNs) has further diversified the inherent challenges of the RRM in telecommunications. The HWN which is a feature of the beyond 3G framework, has introduced more sophisticated technological solutions, due to the heterogeneity of users, services, Quality of Service (QoS) requirements and what not. Therefore, in a heterogeneous wireless network, RRM techniques require more advanced solutions to meet up with the evolving demand.

The utilization of radio resources by subscribers on the network determines the condition of the network. Users requests for diverse services, with different QoS attributes, without any knowledge of the network condition at the time. Also, users aim to maximize their utilities as they utilize the radio resources 'selfishly' [4]. This overall behavior creates a challenge which impedes the efficient utilization of the radio resources, despite the technological advancements in the base stations' architecture and capabilities. An economic approach is proposed to control this behavior, given that users are sensitive to price. The pricing schemes approach introduces an incentive to the network usage. A dynamic pricing scheme can be employed to incentivize users to limit their consumption during peak periods of utilization and are encouraged to use the network during low utilization periods. This 'use-control' is achieved by increasing and reducing prices based on network load conditions.

2.1 Overview of Heterogeneous Wireless Networks (HWN)

Heterogeneous wireless networks (HWNs) can simply be defined as the interworking of different radio access technologies having a pool of resources, which is jointly managed. The RATs include 2G, 3G, WiFi, LTE deployed in macro, micro, femto cells and so on, with each constituting RAT having different capacities and physical characteristics [5]. A HWN is assumed to have a pool of resources belonging to coexisting RATs, which is commonly managed for an efficient radio resource utilization. The Figure 2.1 illustrates a heterogeneous network, consisting 2G, 3G, WIFI, LTE access networks. The RATs have different capacities and capabilities, ideally under the control of a single control entity known as the Common Radio Resource

Management (CRRM) entity.

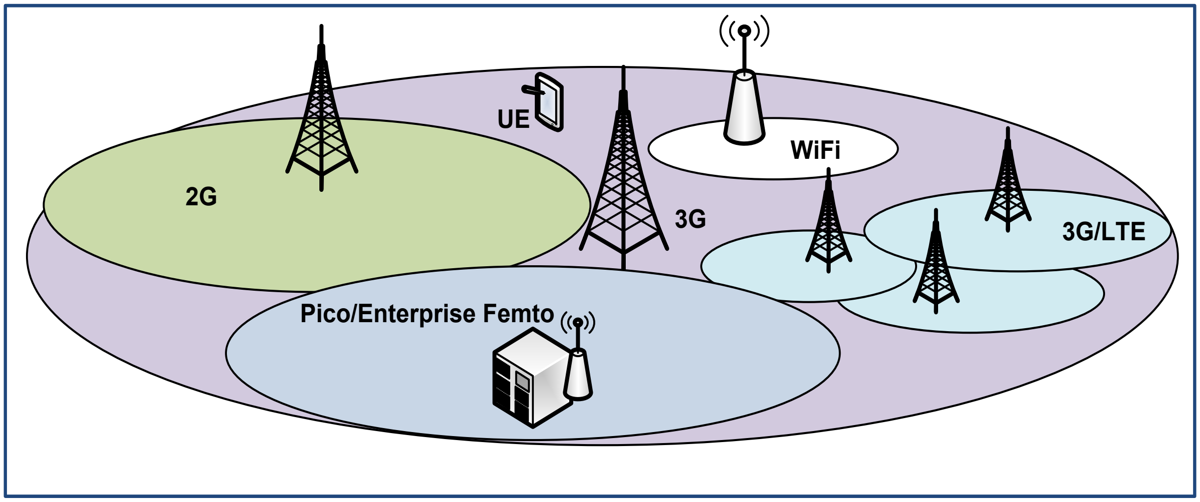

Figure 2-1: Heterogeneous Wireless network illustration

The HWN shown above provides a wide range of possibilities and functionalities to subscribers, leading to a higher aggregate in capacity and better QoS for users. The increasing demand for high bandwidth-consuming applications creates congestion in the heterogeneous networks, despite the higher aggregated capacity available in HWN. The trend in the telecommunication over the years is that demand always meets up with capacity, thereby posing a challenge of matching demand and capacity efficiently. Heterogeneity in the network introduces dynamism arising from multiple dimensions such as propagation conditions, traffic generation conditions, interference conditions etc. Therefore, the dynamic network evolution calls for dynamic management of radio resources resulting from the multiple number of parameters that needs to be analysed.

HWN provides numerous advantages compared to the homogeneous networks and provides benefit to end users and operators as well. The following are the advantages provided by the HWN:

a. HWN provides wider range of capabilities, services and quality than what a single

RAT (homogeneous network) can provide.

b. Users are presented with a wider range of alternatives as they roam the HWN. Multi-mode users can connect to the RAT that suit their requested service.

c. Network operators running HWN can generate higher revenue by exploiting the properties of each individual RAT.

d. Network operators have better opportunity to explore business aspect of the telecommunication networks. Efficient pricing schemes can be developed to attract more users to make connections.

Table 2.1 shows an example of RATs that can coexist in HWN with diverse characteristics in terms of bandwidth, coverage, and application [6].

Table 2-1: Wireless technologies characterised by data rate, range and application

Class	Technology	Data rate	Range	Application
Cellular	2G: CDMA, GSM 2.5G: GPRS, EDGE 3G:UMTS 3.5G: HSDPA 4G: LTE	≤20Kbps 30-90Kbps 2Mbps 0.384-14.4Mbps ≥100Mbps	Cellular Network	Cellular phone, multimedia applications or SMS/MMS
WLAN	ZigBee 802.11a 802.11b 802.11g 802.11n	0.02-0.2Mbps 54Mbps 11Mbps 54Mbps 100Mbps	70-300m 100m 100m 100m 100m	Sensor network LAN Internet

WPAN	802.15 Bluetooth Ultra-Wideband	0.8-1Mbps 50-100Mbps	≤10m 10-30m	Cable replacement Synchronization and transmission of video/audio
WMAN	802.16 WiMAX	70Mbps	50km	Metropolitan area broadband internet

It is worth mentioning that HWNs have gained wide attention today, as they support diverse mobile terminals such as smartphones, phablets and tablets. Some of the mobile terminals enable users to connect multiple radio interfaces, which include but not limited to GSM, 3G, WiMAX, LTE, WLAN and Bluetooth.

2.2 Radio Resource Management in NGWN

Radio resource management strategies enable efficient utilization of the air interface resources in the radio access network. The strategies adopted in managing the scarce radio resources need to be highly optimized to avoid congestion and underutilization. As the telecommunication technologies evolve, the RRM strategies have significantly evolved from the context of single RAT developments, which corresponds to the 2G, 2.5G and 3G to a jointly managed radio resources of coupled networks, termed the heterogeneous wireless networks, HWN (or the next generation networks).

In the next generation wireless networks, the common RRM (CRRM) is responsible for the efficient management of the pool of radio resources made available by the combined RATs. The idea of the CRRM is based on pool of radio resources, belonging to different RATs, but commonly managed. Emerging technologies require the development of CRRM algorithms for the seamless operation of each RATs available on the network. The participating RATs in the HWN is based on specific multiple access mechanism exploiting in turn different orthogonal dimensions, such as frequency, time and code. Furthermore, each overlapping RAT is characterized in terms of coverage, operational cost and Quality of Service capabilities.

The coexistence of different RATs necessitates the common Radio Resource Management (CRRM) for enhanced QoS provisioning and efficient radio resource utilization [7]. They are aimed at maintaining QoS and at large, the quality of experience (QoE) of users. The Call Admission Control (CAC) and Pricing schemes are two of the Joint RRM algorithms. Generally, there are two types of QoS requirements of a call namely packet-level QoS requirements and Connection-level QoS. The CAC is sufficient in improving packet level QoS (in terms of packet delay, average throughput, jitter and packet loss probability) of ongoing connections especially during congestion period. However, CAC is not efficient in improving connection level QoS (in terms of new call blocking and hand off call dropping probabilities) in that it does not provide incentives for users to use shared resources efficiently [8]. The current CAC schemes cannot avoid congestion because they do not provide incentives for users to use channel resources effectively. Therefore, new call blocking and hand-off call dropping probabilities reach high levels during congestion.

The major aim of jointly managing radio resources by the CRRM is to achieve an optimum solution in terms of throughput, cost per packet, development and deployment cost [2]. The operation of the CRRM for this work will adopt a policy-based approach. A policy is a group of rules or criteria that guides the network behaviour based on operators preferential parameters. The policy-based approach enables the operators to modify the CRRM entity for optimizing the functionalities to the degree allowed by the coupling mechanism. With the policy-based approach, operators are able to deploy and correlate business strategies with the overall network actions [2].

The interconnection as well as the interworking of these RATs is made possible through the core network or the backbone networks. Users terminals having multi-interfaces can now connect to different wireless technologies available. An outstanding property of the HWN is in harnessing the best features of each individual network, providing wider range of services and quality than a single entity of homogeneous network.

On the other hand, operators have more opportunity to maximize their revenue through provisioning of a HWN. The revenue can be maximized when a pricing scheme that enhances the efficient utilization of resources is implemented.

In the HWN, local RRM entities perform some decisions inherently in the individual RATs, while the CRRM makes a joint decision based on the locally made decisions. The level of interaction between the local RRM entities and the CRRM may vary depending on the policy adopted or the degree of optimization. There are different possibilities of implementation of CRRM procedures in the HWN. Figure 2.2 shows a low level of interaction, where the CRRM only decides the policy to be adopted in the RRM operations. All RRM measures such as RAT selection algorithms, Hand over algorithms, Admission control, Congestion control, scheduling and power control are handled by the local RRM entity.

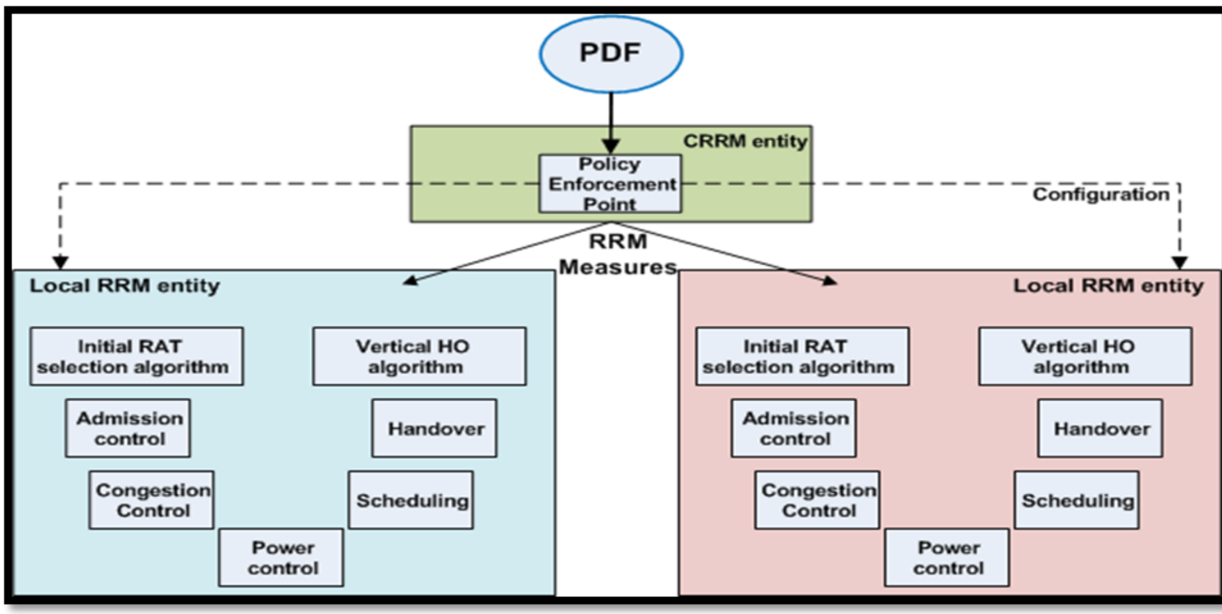

Figure 2-2: Low-level interaction between the CRRM and RRM functions [2]

For a highly sophisticated HWN, the configuration in Figure 2.2 above is not efficient enough because the low interaction between the CRRM and the local RRM entity is limited to the policy specification and update, which occurs on a long-term scale thereby posing a drawback. Higher levels of interactions are achievable which only limit the responsibility of the local RRM entity to power control. The Figure 2.3 shows the configuration where all RRM measurements are jointly controlled by the CRRM. The efficiency of the network is therefore enhanced in terms of response time, where a frequent RAT selection can be performed for a given terminal within the shortest time. Thus, the CRRM also handles congestion control to avoid overload situations in the access networks.

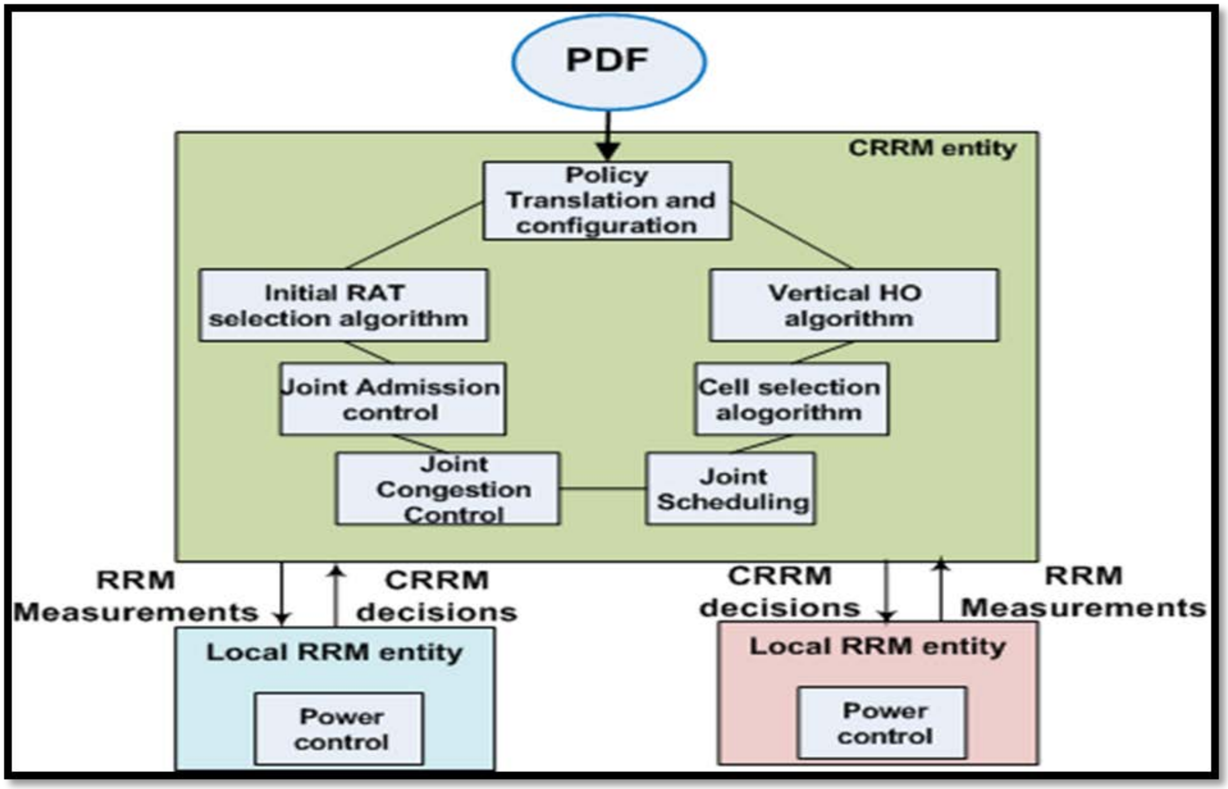

Figure 2-3: High level of interaction between the CRRM and RRM functions [2]

The next section presents the global vision of radio resource management, giving details on the high level of interaction between the network user and the network.

2.2.1 Global Vision of Radio Resource Management

The global vision of resource management in the HWN is a highly interactive mechanism which integrates the user and the network seamlessly. The NGWN, which introduced the 'user centric' paradigm, is depicted in Figure 2.4 below showing the convergent point of users and the network, with network operators continuously engineering their technological prowess.

An efficient framework for HWN involves the following procedures and functionalities: Resource (information) monitoring, Decision making and Decision enforcement. The interaction between the users and the network can be seen in Figure 2.4. Decision making is mainly dependent on resource monitoring and decision enforcement.

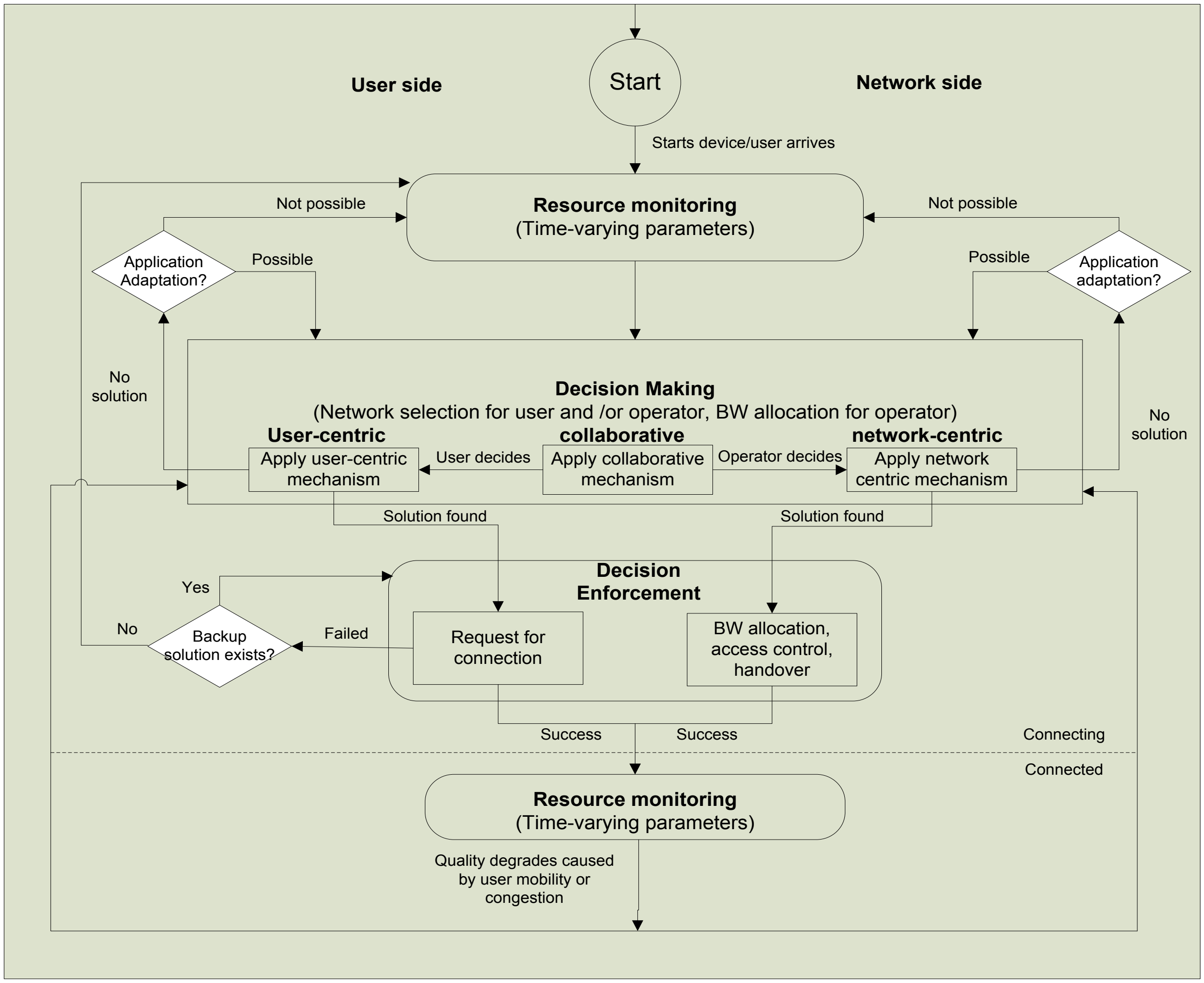

Figure 2-4: Global vision of resource management in HWN [6]

The procedures involved in efficient management of the resources can be explained in the following [6]:

a. **Resource monitoring:** This is the information gathering phase, whereby the information is obtained either from the users, the networks or both. This information is considered as an input for making decisions that enhances the use of the available radio resources. Resource monitoring is done before and after a connection is established. The first monitoring phase is for the purpose of initial network selection and bandwidth allocation. In an event of call request, if the network is unable to allocate bandwidth to the user based on the class of request, the user is advised to modify the request (application adaptation), else user will wait by returning to resource monitoring mode, and until network condition is favorable for the requested call. The second monitoring is for the purpose of observing an ongoing connection in the occurrence of undesirable events such as user mobility or congestion. Network modification will therefore take place due to mobility or network congestion.

b. **Decision making:** Decision making can either be based on the network operators' preferences or at the users' preferences, referred to as network-centric approach and user-centric approach respectively. Collaborative decision making is also possible, called the collaborative approach. The major focus for this research on the HWN is inclined towards the collaborative approach which encourages the equal participation of the 'two parties' in making any decision.

c. **Decision enforcement:** This is the execution phase of the management procedures. It ensures that the connection request to a selected network is successful. On an event of unavailability of connection, it will go back to the monitoring stage and wait for a favorable condition. This occurs when the network refuses a call request in order not to violate the commitment made to ongoing calls. In network-centric approaches, network selection is enforced using admission control mechanisms to filter or direct access to networks according to the decision made in previous step.

2.3 Decision Making Mechanism in Network Selection

Decisions can be made through a network-centric approach or user-centric approach or both, depending on who is making the decision. An efficient HWN environment requires a decision mechanism that does not only integrate the network and the users, but also collaborate the objective of both, in making or arriving at a decision. According to who is benefiting from a decision, the scheme proposed in [6] classifies the solution into three approaches: network centric, user-centric, and collaborative approaches.

2.3.1 Network-Centric Approach:

This approach makes decisions solely on the network conditions and network operator's profit even though some mechanism may also take into consideration user's requirements before making decision. Schemes in this approach deal with how network can optimize its bandwidth and thus, making the bandwidth allocation problem the main concern. The following are examples of network centric based schemes;

- Stochastic programming scheme in some literature addresses the joint resource management, in which user bandwidth is provided by several access networks in HWNs. However, it only supports a single common service with fixed required bandwidth which is not appropriate for a HWN characterized by variety of services along with differentiated bandwidth.
- Game theoretic schemes places the success of individuals on the choices made by other participating agents. The objective is to ensure each network offers maximum bandwidth as available and increase revenue obtained by new connections. The scheme in [9] present a game theoretic scheme within cloud service providers that compete for cloud users. They aim to obtain an optimal price for each cloud service provider that best corresponds to their service qualities and yet remain attractive to cloud users.
- The utility function schemes is the satisfaction derived from the requested service. The scheme in [10] proposes a utility-based dynamic pricing scheme for improving network operators' revenue. Users' utility (satisfaction) can translate to the QoE of the subscriber. For this research, the user and operator utility function is used to evaluate the performance of the proposed scheme.

2.3.2 User-Centric Approach:

Decisions are made at user terminals and they are based only on user's profit without considering network load balancing or other users. This is majorly a network selection problem, with the objective of finding the most profitable network for user's application. Users are only concerned about maximizing their utilities, not bordered about the network condition, thus leading to congestion and quality degradation of ongoing network users. On occasions whereby the network block users due to one reason or the other, users will have to process the call request again, thereby resulting in higher energy consumption. The following are examples of user centric techniques for decision making;

- Analytical hierarchy process and grey relational analysis; An Analytical Hierarchy Process (AHP) is employed for objective criteria weighting. An order preference technique based on Grey Relational Analysis (GRA) is then applied to rank the evaluation alternatives. AHP and GRA are techniques employed in Multiple-Attribute Decision Making (MADM), which involves making preference decisions (e.g. evaluation, prioritization, selection) over the available alternatives that are characterized by multiple, usually conflicting attributes.

- Consumer surplus; In economics, the consumer surplus is the amount that consumers benefit by being able to purchase a product for a price that is less than what they would be willing to pay. Today's HWN characterized by real-time multimedia application cannot be efficiently managed by this scheme, because it is designed for non-real-time multimedia applications. However, the concept consumer surplus remains interesting as it can also be exploited using different parameters in real time multimedia applications available in the HWNs.

2.3.3 Collaborative Approach:

This approach is considered to be the most compromising in terms of profit because it takes into consideration the maximization of utilities and revenue of users and operators respectively. It can be considered as the integration of both the user-centric and network-centric approaches, discussed earlier. The users' preference is weighted along with the operators' preference, then an equilibrium is obtained through iterative measures with the objective of controlling congestion and enhancing users' utility and operators' revenue. This is the major focus of this research. More details on techniques employed in reaching users and operators utility and revenue enhancement respectively, are in upcoming chapters.

Heterogeneous wireless network environment requires a decision mechanism solution that will not only provide access to the users, but also collaborate the preference of both provider and the user, in making or arriving at a decision. According to who is benefiting from a decision, K Piamrat *et al* in [6], classify the solution into three approaches: network centric, user-centric, and collaborative approaches.

The telecommunication market has experienced remarkable shifts and strategies from business plans to technological advancements as evolution continues. Previous disconnected systems are now integrated and this thereby continuously transform the Operation Support Systems (OSS) and Billing Support System (BSS) environments [11]. The features of the HWN and various users demand drive the transformation of the OSS and BSS.

Pricing a network is an important aspect of the network management, which determines the revenue obtained by the operator and how the users perceive the network. Network service providers adopt price policies, which enable them to obtain revenue for services provided. Pricing of the network services may differ among operators, though offering same services. Users' price sensitivity plays a major role in attracting users to a particular network and on the other hand, the network QoS guarantee is also important. Users aim to maximize both QoS and monetary utilities as they crave for the network resources [12].

In economic terms, the telecommunications market can be referred to as an oligopolistic market. An oligopolistic market describes a scenario where few sellers sell to many buyers. The sellers here represent the network operators and buyers are the users. This creates a competitive platform between operators, where the operator perceived to offer the best prices and QoS guarantee, has more users. An intelligent marketing strategy for an operator will be to consider what users perceive about rate of calls in comparison to their competitors. Different operators may adopt different pricing policy. Policy entails outlined rules of how the usage of radio resources should be billed. Due to the ever-evolving telecommunication market and competition, policies should not be static, therefore a dynamic pricing policy is suitable. For example, a software based programmable dynamic pricing scheme provides flexibility to operators to modify price policies implemented on the network, to meet up with diverse users demand and to enhance profitability [13]. It introduces scalability, efficiency and flexibility to the dynamically priced network, especially for real time charging and pricing, where the network utilization levels keep changing.

The drivers of policy management are based on some factors which have spurred investments in next generation OSS and billing systems over recent years. These market shifts also apply to the policy management level as operators look for capabilities that enable their new services and new business models. Next generation policy management solution can support a number of capabilities that are critical to the next generation services, including the following; Convergence, IP-based services, Service differentiation, Customer care and marketing opportunities, third-party content and partner support, network/service resource management to mention a few [11].

The next generation RATs are expected to operate efficiently amid the complexities presented by the HWN features. In this context, the operators must strategically adopt a highly intelligent network functionality to manage the radio resources. The word thrown around recently for such sophistication is the self-organizing networks (SON). This is considered as a driver to achieve reduction in complexity, cost of network management, cost of operation and improved interoperability [14]. It is envisioned that SON functionalities will become commercially available with the operation of the 4G networks.

2.4 Reinforcement learning algorithm

Reinforcement learning (RL) is an aspect of machine learning which entails an 'agent' taking some actions in an environment to yield some expected reward. The RL enables the agent to learn some set of policy, aimed at maximizing the total associated reward. There are various methods and algorithms for policy evaluation in literature, such as iterative policy evaluation, value iteration and linear programming (Q-learning). For this research, the Q-learning algorithm was chosen after evaluating the pros and cons of the three types of reinforcement algorithms mentioned above. Table 2.2 shows the pros and cons of the algorithms mentioned which led to the choice of Q-learning algorithm for this research.

Table 2-2: Pros and cons of policy evaluation algorithms

ALGORITHM	**PROS**	**CONS**
Value Iteration	Simple to execute if true value of each state is known	Gives outcome of values of each state (instead of *policy*) which is not our goal.
Policy Iteration	Works well in determining optimal policy	A great deal of knowledge of the environment is required, which might not be at our disposal
**Q-Learning*	*A 'model-free' learning, combines learning and execution, simultaneously in any given environment having states and possible actions*	Due to learning and update process, same states may be visited several times before finally obtaining an optimal policy

The major highlight of choosing the Q-learning technique instead of any of the other technique is because of the dynamics of the HWN considered. Information about the HWN is not readily available. Also, bearing in mind that, the HWN comprising RATs with different capacities and capabilities are individually accessed by users. This makes it a highly dynamic system Therefore, the use of Q-learning technique which support learning and execution simultaneously is important, to enable the HWN switch between states and actions in an efficient way.

2.5 Joint Call Admission Control (JCAC) Mechanisms

The heterogeneous feature of NGWN necessitates the Joint Call Admission Control (JCAC) mechanism. Heterogeneity creates more sophisticated ideology and approach to utilizing the pool of radio resources available in the network. The homogeneous architectures of the Call Admission Control (CAC) is therefore not efficient enough to manage the features on the NGWN.

Two basic functions of the JCAC are [7]:

a. Call admission decision and

b. RAT selection decision

The basic functions of the JCAC highlighted above can be explained in details as follows:

- Firstly, determines whether a call request can be admitted into the HWN or not,

- Afterwards decides which of the constituent RATs in the HWN is capable of handling the requested call given a performance target which may include, but not limited to; access cost, security, data rate, mobility, energy efficiency and so on [15].

JCAC algorithms are necessary for efficient utilization of radio resources, consistent provisioning of QoS across different RATs, overall stability of network, enhancement of users' satisfaction, and increase in operators' revenue [7].

2.5.1 Requirements of JCAC Algorithms

The following are the requirements for an efficient JCAC algorithm for overall benefit of users and operators as given in [7]: multi service, efficiency, simplicity, high-execution speed, scalability and stability.

2.6 Quality of Service (QoS) Solutions in NGWN

The NGWN that transports multimedia traffic creates the need for QoS solutions which recognize the requirements of the network to provide different QoS media and subscriber property to the different traffic flow available in the HWN. High bandwidth consuming services and applications that run on the HWN require high QoS that results in a high QoE for the subscribers, despite the growing traffic volume [16]. Different media types such as video, voice and data demand different QoS profiles such as premium, best effort and so on with different network operator requirements over different time frames.

The business models and strategy of operators require modifications that will suit the need of subscribers whose demand is ever increasing in the telecommunication market place. The approach in [16] suggests 'QoS differentiation solutions' that will provide tools that not only support the requisite changes, but also allow operators to anticipate upcoming requirements. Bearing in mind that each operator and market differs from each other, the need for an operator to understand what is relevant will aid profitability and efficiency.

The benefits and objectives of QoS differentiation depend on the network operator needs. Some operator may choose to fulfil different objectives simultaneously while most operators are concerned about realizing common benefits such as maintaining high QoS, ensuring efficient use of resources, monitoring traffic streams, and flexible support service. Maintaining high QoS is particularly important for real-time services and bandwidth intensive services, which requires minimal end-to-end delay and jitter while asynchronous applications may require high throughput. Monitoring traffic streams allows operators to optimize usage of their network resources and capacity upgrades.

Standards help the mapping of services and applications to QoS profiles or QoS markings. However, operators also need to create the mappings that provide the best fit with their business strategy. The proposed solutions in [16] are bandwidth limitation solution and prioritization solutions, which is explained in the next section.

2.6.1 Bandwidth Limitation Solutions

The approach adopted here entails operators' selection of bandwidth limitations to encourage subscribers to use certain applications at congestion times, if the network load can be evenly distributed throughout the day, then resources will be used in the most efficient way. In the long run subscribers will have access to a better and cheaper service. Classification of users into VIPs and budget users can also enhance the assignment of bit-rates as shown in Figure 2.5. Subscribers who require high maximum bit-rates will pay more than those that don't require such. Consequently, operators will increase their revenue significantly.

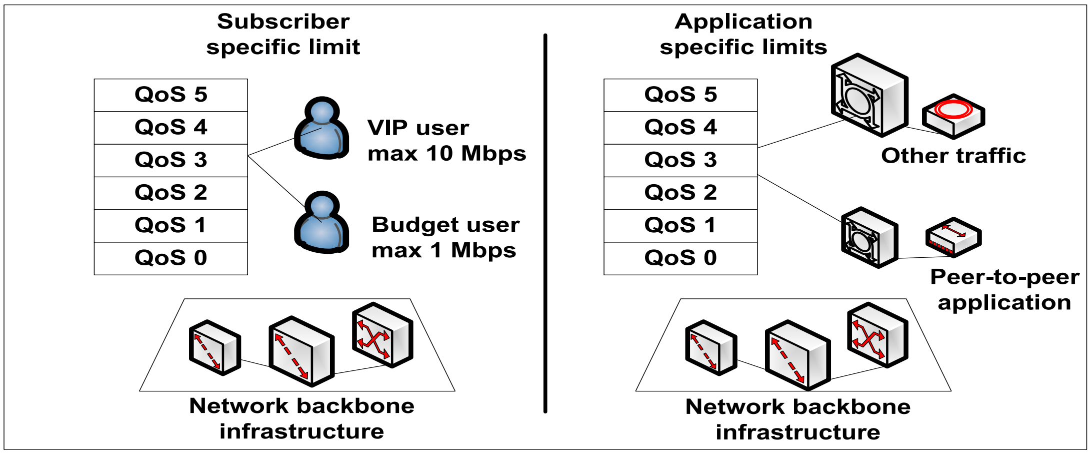

Figure 2-5: Bandwidth limitation solutions [16]

2.6.2 Prioritization Solutions

Prioritization entails operators grouping subscribers into categories and assigning specified price tags for services requested. Some services and applications can even be categorized by time of use, for example applications that place heavy load on the network such as point-to-point (P2P) can be priced in a way that they are only used at night. Figure 2.5 above describes the prioritization of users, having VIP and budget users. Figure 2.6 shows QoS differentiation strategies for subscribers, applications and service providers having Service Level Agreement (SLA) with the network operator.

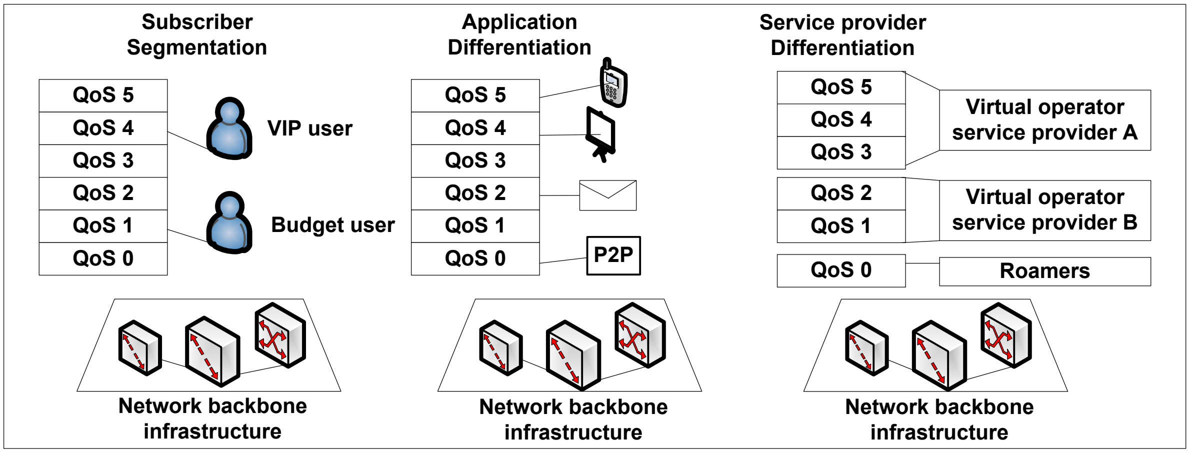

Figure 2-6: QoS differentiation strategies [16]

A subset of prioritization is the subscriber segmentation. Important subscribers such as enterprises and large organizations will have the most demanding requirements. The basis of subscriber segmentation is to be able to charge a premium price for premium services. Operators can also follow the traffic volumes and throughputs of subscribers segments using the QoS specific performance counters in the access network elements. Subscribers' segmentation scenarios will normally be used in markets where there are high-income differences between consumers [13]. Charging of segmented subscribers may differ, where a segment of subscribers charged based on volume and other charged on a flat rate basis - the volume based subscribers should have a higher priority.

The scarce network resources requires an optimal management which can be realized by application and service differentiation. Non real-time applications tolerate much longer delays than the real-time applications, prioritization of the real time packets can therefore be efficient when there is congestion [13]. Application differentiation enables monitoring of applications as they flow along the network. Consequently, operators achieve high revenue through the creation of these platforms that make customers see better application performance that benefits them.

2.6.3 Technical Components of QoS Solutions

The technical components of QoS differentiation as described in [16] comprises of the QoS management, QoS control and QoS enforcement. Figure 2.7 shows how the components interwork to achieve the QoS goals. The network elements maintain QoS profile specific counters and send them to the management tools for visualization and additional network optimization. QoS control refers to the intelligence that maps the subscribers or applications to the desired QoS [13]. QoS enforcement refers to the mechanisms that treat the connections or flows differently as well as the efficient allocation of network resources. Examples include queuing mechanisms plus shaping, policing and radio resource management algorithms.

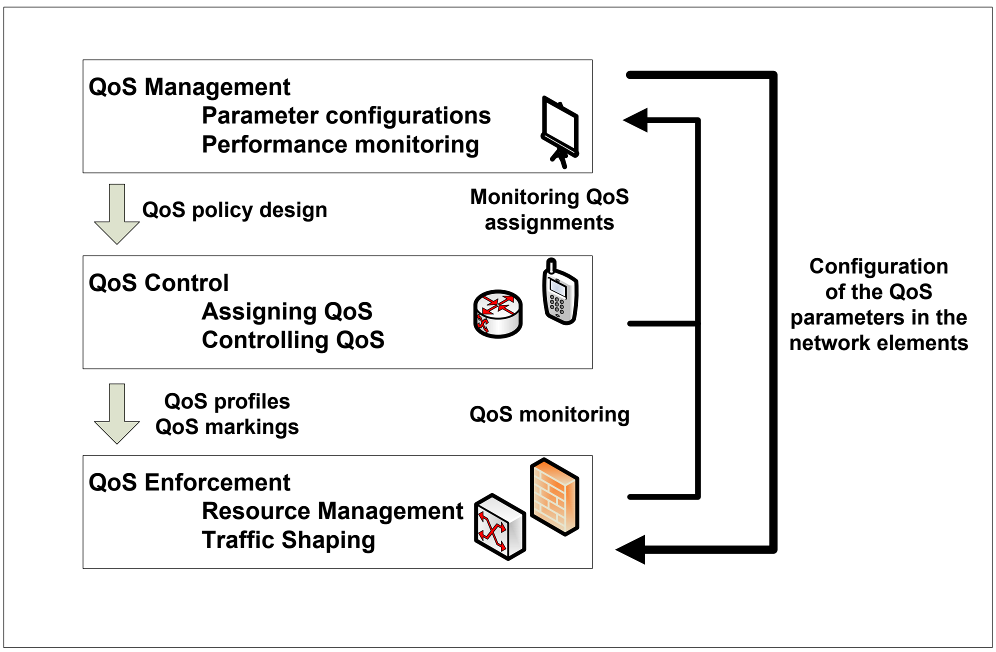

Figure 2-7: Components of a QoS differentiation solution and their relationships [16]

It is envisioned that many types of terminals with sophisticated capabilities will emerge, running a wide range of applications, which translates to increase in diversity of QoS capabilities. Users will download diverse applications to their terminals, making the impact of software developers more significant on the QoS capabilities of their applications. An operator may choose the following two important measures [13];

- Relying on terminal request on the availability of device with requisite functionality: This is achievable if the terminals are operator branded terminals running on operator-defined applications. The operator is able to control what type of request is being made and charge more for higher QoS.

- Ignoring terminal requests or indicated QoS requirements: This is feasible if the operator doesn't earn higher revenue even if higher QoS is allocated. This applies to a strategy based on flat rate charging and this is a typical near-term business model.

QoS differentiation provides numerous and flexible ways of allocating and managing network resources. It is also used to enhance performance-monitoring capabilities. In addition, QoS mechanisms can be used to support different pricing scenarios and thereby influencing subscribers' usage and loyalty. Many QoS mechanisms have gone through stages of standardization and implementation. However, the need for additional functionality that is provided by differentiation solutions will become more relevant as demand for high bandwidth consuming services and applications increases the network traffic levels.

The best solutions can be achieved by developing an efficient operators' business model and strategy. This includes exploring pricing schemes that can be integrated into an optimum QoS differentiation solutions, at the long run encouraging the efficient use of resources and customers' satisfaction.

2.7 Congestion in Heterogeneous Wireless Networks

In a telecommunication network, there is an assumption that there are infinite numbers of subscribers, accessing a finite number of channels. The channels refer to network element that enables subscribers get access to radio resources. A new call request that is blocked or handoff call dropped, due to unavailability of resource, degrade in quality of service, delay and jitter is an indication of congestion in the network. The high demand for access to these channels creates congestion in the heterogeneous wireless networks.

Subscribers still 'crave' for more bandwidth consuming services existing on the HWN like high quality (HQ) voice and gaming, HD video, real-time video and video streaming.

Consequently, demand for capacity increases and congestion occurs in the network. Therefore, congestion control in HWN remains an issue. The following subsections examine the effect of congestion, methods of congestion control and economic approach for congestion control in heterogeneous wireless networks.

2.7.1 Effect of Congestion in Heterogeneous Wireless Networks

When the demand for the radio resources supersedes the available capacity, the network experiences drawback from optimal operation. This leads to the degradation of quality of services guaranteed to the subscribers. Subsequently increasing the call blocking and call dropping probabilities, delay and jitter and so on. Operators need to minimize the effect of congestion in order to meet QoS requirements of subscribers.

2.7.2 Methods of Congestion Control in Heterogeneous Wireless Networks

The effect of congestion on the network is observed by the use of various metrics such as call blocking and call dropping probabilities, throughput, end-to-end delay or latency, packet loss probability etc. Operators' choice of methods of controlling congestion should ensure improvement on the network utilization and profit enhancement. The focus of this research is to employ dynamic pricing to control congestion, while enhancing operators and users' utility.

2.7.3 Economic Approach for Congestion Control

From the ongoing review, the focal point of the discussion is utility, both users and operators envisage satisfaction monetarily, even as radio resources are utilized. Economic factors therefore play a major role in obtaining this satisfaction. From the ongoing deductions, an economic approach to control congestion is adopted in this research. It suggests an external control of congestion rather than on the network elements, by introducing incentives into the usage of radio resources. Network subscribers differ in terms of age, sex, education and budget, therefore their responses to prices, as well as incentives will differ [17]. An economic approach from the price point of view, considers the diversity of users' life style. The use of demography provides valuable information to service providers on the type of service, price and access technology to be deployed in any area, in a cost-effective manner. These data may be obtained during the radio network-planning phase. Areas with a high population of educated subscribers will be more likely to pay higher for internet access and voice calls, whereas rural areas, which have subscribers with low educational level, will prioritize voice services at affordable prices.

However, a service provider must ensure an economically efficient pricing, which will make sure that no single geographical area will have the same type of users. An economically efficient pricing scheme will ensure that the majority of users are treated fairly and equally. An assumption of common pool of resources scenario is examined whereby the finite common-pool of resources are accessible by any user and users are assumed to be short-termed and 'profit-maximizing actors' [18]. Users of resources always aim to maximize their utilities, which may therefore cause some greedy users to hold on to a constrained pool of resource longer than necessary, leading to 'the tragedy of the commons'. An economically efficient scheme in terms of resource allocation and price sensitivity model (PSM) is defined as follows:

a. Economically Efficient Resource Allocation

For a network to be considered economically efficient in allocation of resources, it must not be pareto-efficient. A pareto-efficient system is one with economic equilibrium in which it is impossible to change the allocation of resources without improving the lot of one agent at the expense of another. In other words, it is a system that makes the service obtained by a participant better, but at the detriment of others [19]. The allocation with the best economic efficiency is that which when given an allocation, results in a pareto improvement. In technical terms-, a new call or handoff call accepted into a resource-constrained network must not violate the service commitments made to the already admitted calls (i.e. a granted access of a new call into radio resources must not be detrimental to the existing ones). If this condition is met, then a system is said to be economically efficient.

b. The Traditional Price Sensitivity Model (PSM) Approach- The Van Westendorp PSM

PSM provides a trade-off to tackling the effect of pricing challenges in economics and aids understanding of customers. The traditional PSM approach asks four price-related questions, which are then evaluated as a series of four cumulative distributions, one distribution for each question. The assumptions are that a product (service) has a price demarcation; Let Hp and Lp be high price and low price respectively, and an affordable price, Ap, the standard question formats can vary, but generally take the following form [20]:

1. At what price would you consider the product too expensive that you would not consider buying it? -too expensive (Ap<<Hp)
2. At what price would you consider the product to be priced such that you would feel the quality could not be very good? -too cheap; Credibility in doubt. (Ap>>Lp)
3. At what price would you consider the product starting to get expensive, so that it is not out of the question but you would have to give some thought to buying it? (Expensive high side) (Ap<=Hp)
4. At what price would you consider the product to be a bargain- a great buy for the money? (cheap/good value) (Ap>=Hp)

The fourth question highlighted above could be proposed as the optimal price for the subscriber while question three is close to being the optimal price for the operator. Determining a common point between the third and fourth questions helps to combine both user's and operator's preference in selecting optimal price during congestion. 'Optimal price' is like the two sides of the same coin- it is the price that enhances both users' and operators' utility. The social fairness of a network is determined by how much the user's utility is enhanced [21]. To achieve this objective, operators should pay cognizance to subscribers' response. Network users are the major determinant of the revenue generated by service providers. Therefore, a pricing scheme that encourages users to make connection request most of the time will yield greater returns on revenue.

The Van-Westendorp PSM (VPSM) highlights the possibility of users having the liberty to abandon any system if they feel price is not affordable. Abandoned systems apparently lead to wastage of resources and losses on the operator's revenue, after a prolonged situation, the provider may lose loyal subscribers to competitors. As a network provider or operator, the major objective is to ensure that network resources are optimally utilized, users' and operators' utility is enhanced. When users' utility is enhanced then the network is said to be socially fair to users.

2.8 Role of Policy Management in HWN

Subscribers remain the major reason for the unprecedented advancement in the telecommunication industry. Customers are becoming more sophisticated, demanding more from their service providers. More competitive pricing, better QoS, wide range of services and more applications are on the trend presently, with no end in view. Technology has also adapted to this demands, through obvious advances in bandwidth capabilities, evolution of network standards, flexibility and robustness in telecommunication software and so on. The interaction between subscribers and the network is undergoing a continuous change in methods of approach and integration. The changing interaction is responsible for the modifications witnessed so far in terms of capability of the network and the requirements of the customer, therein lies the innovation in form of new services and a new focus on customer experience.

The key word- 'policy management' becomes critical in achieving an equilibrium between the customers' experience and operators' revenue. As explained in [11] the service providers' interest in next generation policy management solutions is on the rise, driven by the following factors:

- Demand for convergent services, which is driving interest in convergent Operation Support Systems (OSS) and Billing Support Systems (BSS) platforms that support multiple networks, services, devices, applications and content,
- QoS requirements associated with IP-based services,
- The need for service differentiation in a competitive market,
- Managing the customer experience and improving customer loyalty,
- Managing third-party content and applications,
- Maximizing network and service resources, and so on

Policy management refers to the systems and processes associated with ensuring that various types of network traffic receive the availability and bandwidth as the radio resources are being utilized. Policy management capabilities have enabled network managers to set static rules that controls the priority given to traffic based on variables such as time of the day [11]. Traditional policy management functions generally fall into the following categories [16]:

- Traffic shaping: Using local rules on routers to balance network load and accommodate service level agreements (SLAs)

- QoS management: setting rules for the allocation of bandwidth per service

Figure 2.8 shows the evolution of policy management over the years. Policy management has extended beyond service providers sole control, instead, operators are adopting policy management solutions that support the new realm of capabilities based on ability to manage policy decisions according to dynamic criteria which include subscribers choices. As a result, operators are able to create a personalized set of services that optimize customer's requirements, concurrently with the specific type of network that the customer is utilizing, ultimately optimizing the QoE of the subscriber.

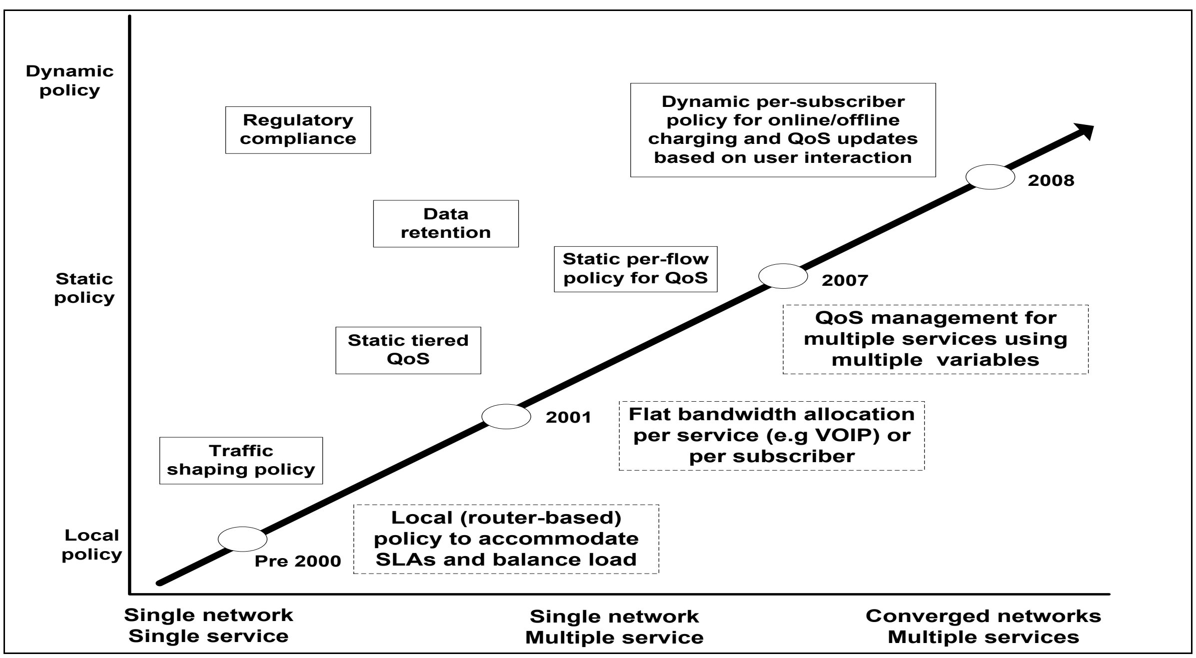

Figure 2-8: The Evolution of Policy Management [11]

Over the years policy management has been limited to static network based functions such as traffic management or basic QoS. The functions of traditional policy management, such as network profile lookup, authentication, and configuration occur at the network layer. This network-based approach has a number of limitations which includes; management challenges, lack of support for multiple access network types, capability limitations, rules limitations and so on.

A new generation of policy management solutions can address the limitations stated above. The policy management solutions ensures transactions are managed at both network and at the service layer. As disaggregation increases between the services and the network, policy will become an important 'bridge' between the network and Information Technology (IT) realms. Policy management can adopt same approaches in network realms to the IT realms, thereby enabling the operators set policy parameter both at the service and network layer.

The drivers of policy management are based on some factors which have spurred investments in next generation OSS and billing systems over the years. These market shifts also apply to the policy management level as operators look for capabilities to make their new services and new business models lucrative. Next generation policy management solutions can support many capabilities that are of great importance to the next generation services, which includes the following; Convergence, IP-based services, Service differentiation, Customer care and marketing opportunities, third-party content and partner support, network/service resource management to mention a few. The flexibility and scalability feature of a next generation policy management system presents creative ways for operators to monetize their network resources and as well as their customer value by enabling them to control services on a per-subscriber and per-service basis

2.8.1 Key Features and Functionality of Next Generation Policy Management System

The next generation policy management system provides features that are benefiting to operators and will highly motivate them to implement these capabilities. Despite pressures to get new services up and running as quickly as possible and to reflect on returns of their network and

OSS investments, operators must view policy management as a strategic enterprise-wide initiative as opposed to a short-term stopgap measure. Policy management decisions are critical to the growth of operators, therefore operators must take note of the following important features when making those decisions [11]; Centralization, Integration Capabilities, Flexibility, Scalability, Standards Compliance.

Operators keen on growth and profitability must learn how to monetize their asset. Policy management is at the forefront of its ability to do so. By effectively integrating network resources information at the network layer together with subscriber and service-specific information at the IT layer, Openet's Policy Manager, can enable operators to extract value from every transaction that occurs on their network while optimizing the customer experience.

The telecommunication market has experienced a remarkable shift alongside strategies, from business plans to technological advancements as evolution continues. Previous disconnected systems are being integrated that continuously transform the OSS and BSS environments. The shifts are discussed in detail below [11]:

- **Deregulation:** Deregulation of the telecommunications market has occurred across most countries over the last decade. Privatization era is also characterized by this deregulation, where the government-owned infrastructures and utilities are sold or leased to private firms. The competition introduced by privatization has driven prices in the major markets while encouraging operators to maximize their revenue by increasing efficiency and lowering their internal costs. This has driven the interest in the elimination of inefficient OSS silos that are replaced by integrated solutions.

- **Competition:** Fierce competition has emerged due to the prospects of the market creating a new breed of players that are interested in the market with the diversification of operators providing a 'cross-breed' of services. For example wireline operators are offering video services over their fiber optics networks, cable operators are adding wireless services to their bundles, wireless operators are providing high-speed data services via technologies such as Worldwide Interoperability for Microwave Access (WiMAX), and all three categories are seeing new competitors such as Mobile Virtual Network Operators (MVNOs) and content providers edge into their market space as well. The initial response is always a ‘price war’, more sophisticated service providers recognize that differentiating the quality and range of services offered represents a better value proposition.

- **Network transformation:** The network architectures have also experienced some major transformation aimed at meeting up with the demand and efficiency. For example a service was embedded in the network it operated on, essentially the service was the network. This architecture presented a bottle neck in the delivery and creation time, and was also expensive. The development of distributed, layered network architectures such as IMS (IP Multimedia services) has changed that by separating the services from the network and thus replacing this traditional service creation and delivery environments with more flexible, real-time service creation capabilities.

- **Usage requirements:** As services and application increasingly advance, they also become bandwidth-intensive. These new demands on the network are often generated by a small subset of users, and operators must either endlessly invest in the network to support these users’ requirements or find a way to manage their network usage to avoid network resources’ abuse. Examples include the blackberry and smart phones users that require an enormous amount of network resources because of the applications running on them and their service capabilities.

- **Customer demands:** The subscribers who are the major reason for these shifts, always crave for better services from the network operators. Assumptions of the reliability of wireless and IP services have changed over the last few years, with consumers of these services increasingly expecting the same quality of service as they have received from the circuit-switched wireline network. At the same time, customers are demanding more personalized services that address their specific needs, particularly as end user devices become more sophisticated as mentioned earlier. This has driven interest in capabilities such as fixed-mobile convergence, or availability of services regardless of device type.

2.9 Pricing the Heterogeneous Wireless Network-Operators and Users' Perspective

In general, operators translate price as an amount charged to meet maintenance cost and keeping the network up and running, while users see price as the amount they give in exchange for the worth of the network service. Both perspectives can be interpreted as 'two sides of the same coin' as mentioned earlier. Furthermore, the operator can employ pricing to control users' behaviour. The following subsection presents the review of pricing scheme and the benefits of integrating dynamic pricing scheme.

2.9.1 Review of Pricing Schemes

Pricing schemes (PS) are designed to offer profitable business to the wireless service providers (SPs) as well as to create favourable services to subscribers and eventually to get charged according to their service usage [21]. Broad classification of the pricing scheme is the Flat rate and Parameter-based pricing schemes as shown in Figure 2.9.

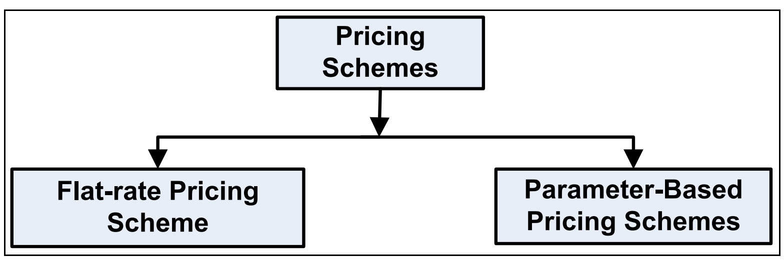

Figure 2-9: Classification of pricing schemes [13]

In the flat rate pricing schemes, SPs set price to a session, independently of the network conditions, such as the traffic variations, the usage, the capacity, the actual time the user spends in the network and type of service. The flat rate pricing schemes are no longer used by SPs because it makes little profit and lead to overpriced events. Flat rate pricing schemes present an unfair deal to users, because the network operators charge same price regardless of whether their QoS requirements are met [13]. In other to overcome these drawbacks inherent in the flat rate pricing schemes, the parameter based pricing scheme(s) was proposed. Parameter-based pricing presents a fair deal to users, in that users get charged as they utilize the radio resources. It aims to maximize providers' revenue as they meet the QoS requirement of users, yielding subscribers' satisfaction.

For the purpose of this research, it is important to explain further classifications of the parameter-based pricing schemes. Parameter-based pricing schemes are further classified into two groups namely Static and Dynamic pricing schemes. The static pricing scheme sets price in a static way whereby subscribers are charged with a predefined price for the service they use, despite the variations of the network resources, available bandwidth, and the number of services offered or the usage of network resources. Figure 2.10 shows further classification of parameter-based pricing schemes.

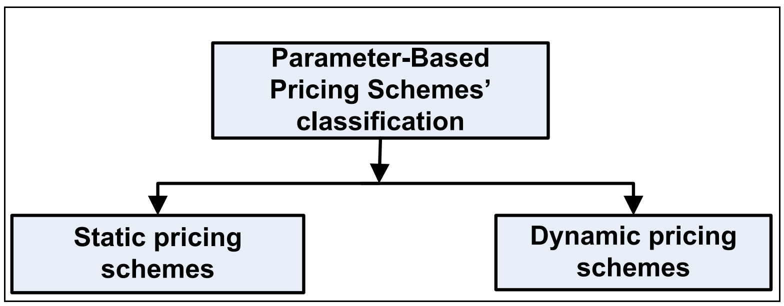

Figure 2-10: Parameter-based pricing schemes' classification [13]

Static pricing scheme, like the flat rate pricing scheme creates a level of unfairness to the subscribers and it is therefore not suitable in meeting users' needs or satisfaction. Pricing in a static way translates to users being charged whether or not they fully utilize their allocated radio resources. The Dynamic Pricing scheme, which is the focus of this work, provides the assurance of users' satisfaction and it varies the price of service according to system utilization. It enables SPs to modify and prioritize the mobile subscribers' services, according to the variation of the subscribers networking demands, which lead to profitable business. Sarah K *et al* in [22], explored the effects of flat rate pricing and dynamic pricing, benchmarking the dynamic pricing model in comparison to the flat rate pricing, better user utility and improved system performance were shown in the results obtained. SPs prefer Dynamic pricing schemes because it adapts easily during the interconnection of HWN. In addition, mobile subscribers, through dynamic pricing are able to select their preferable Class of Service (CoS) and get charged based on their radio resource usage.

In scheme [4], a new dynamic pricing scheme that integrates pricing with call admission control is presented. The system contains two blocks which are the pricing entity and call admission block. The general flowchart diagram for pricing homogeneous networks is shown in Figure 2.11. An overview of call admission control process and price evaluation event is explained in the flowchart.

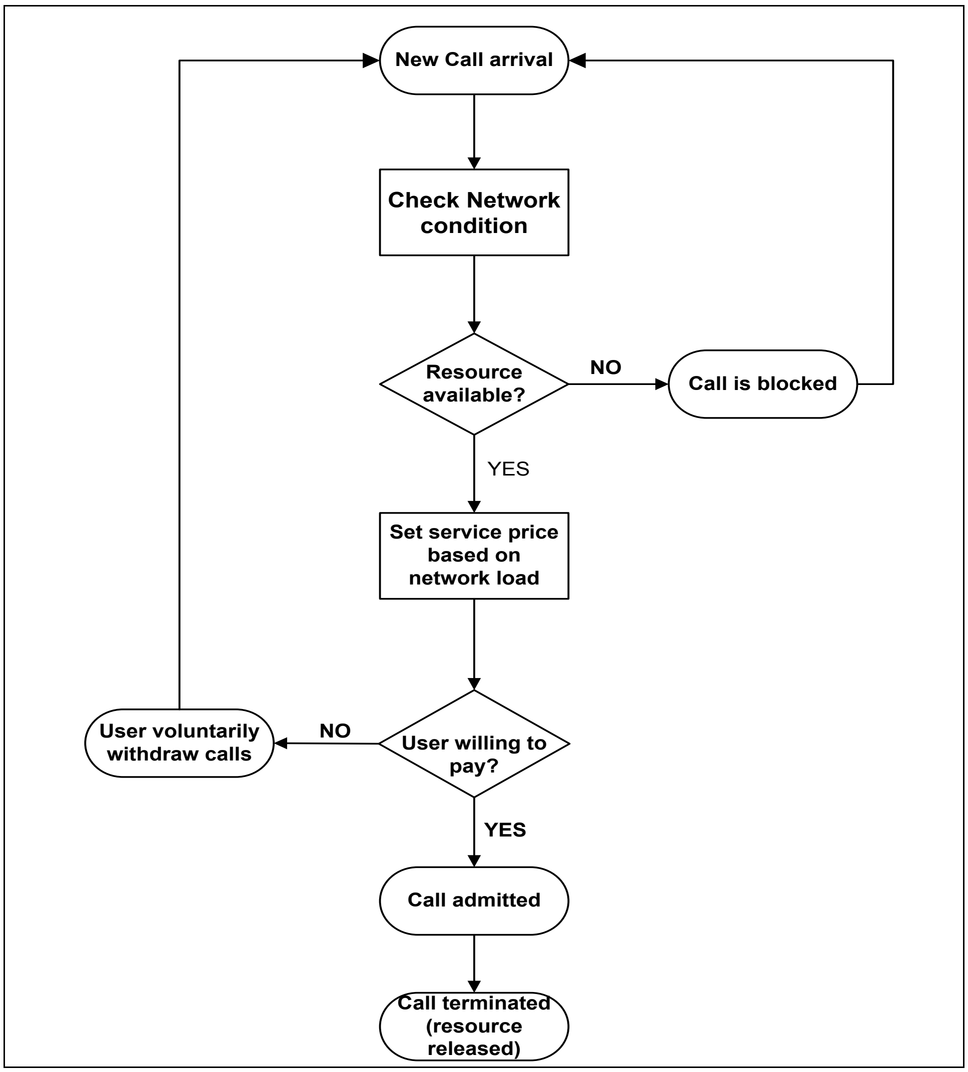

Figure 2-11: General pricing scheme flowchart for homogeneous networks

An efficient pricing scheme is the one capable of setting fair prices of service to subscribers and which ensure the efficient utilization of radio resources. The pricing schemes are usually integrated with the conventional call admission control (CAC) schemes [8], to achieve a more efficient network. On the other hand, some pricing schemes suggest setting dynamic price only during peak period of the day. However, this reduces the operators' opportunity of increasing revenue, because a separate treatment of congestion as a function of time or network usage is not efficient in heterogeneous wireless networks. Pricing a network is usual based on policy adoption, which differs with service providers. In [21] the dynamic pricing schemes are subdivided based on the methods of implementation. Figure 2.12 shows the further subdivisions available in the dynamic pricing schemes.

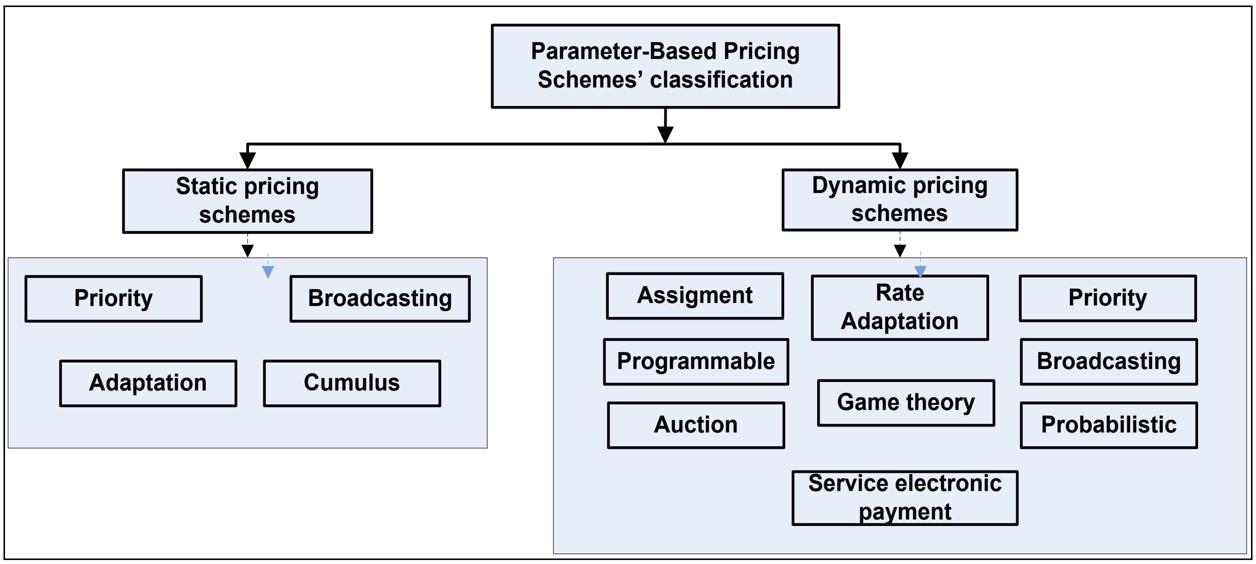

Figure 2-12: Subdivision of parameter-based pricing schemes' classification [13]

The proposed pricing scheme in this work adopts the programmable pricing schemes (a subdivision of dynamic pricing scheme). It is a policy based pricing scheme, which sets prices of service according to predefined set of rules. The proposed pricing scheme aims at enhancing users' utility thereby introducing the WTP inclusion along with the predefined rules when evaluating service price.

a. **Programmable pricing schemes:** A programmable dynamic pricing scheme is a software based pricing mechanism that provides flexibility to operators to modify price policies implemented on the network to meet up with diverse users' demand and to enhance profit.

It introduce scalability, efficiency and flexibility to the dynamically priced network, especially for real time charging and pricing, where the network utilization levels keep changing. The general mode of operation of a programmable pricing scheme can be summarized as follows:

- Service prices are charged based on calibrated monetary units which are determined by prevailing network load,
- The price of service affects the users response to network utilization, due to users' price sensitivity, users limit consumption of radio resource when the price of connection is high and consume more at lower prices,
- The pool of resources is limited, meaning the number of calls that can be accommodated is limited and calls will be dropped or blocked when resources are no longer available,
- An insight is obtained by using a demand model, which determines the arrival rate of users,
- With the prevailing arrival rate, an optimal pricing policy is determined which is aimed at enhancing users' and operators' utility.

Network service providers adopt price policies, which enable them to obtain revenue for the services provided. Pricing of the network services may differ, though offering same services. The pricing algorithms are implemented in the Mobile switching centre of a GSM network, while in an Evolved Packet Core (EPC) network, the policy and charging rules function (PCRF) handle real-time charging rules and functions for each service in the network. The PCRF is a software component (node) where SPs implement a multitude of real-time charging rules/functions for each service in the network and IMS or EPC core networks [23]. Rules may differ based on a variety of conditions such as customer SLA, time of day, or network conditions. In addition, it handles the real-time management of resources, in synchronism with subscribers and applications.

2.9.2 Benefit of Dynamic Pricing Scheme Integration

The pricing schemes are advantageous to the seamless operation and efficacy of the network. Highlighted below are the two major advantages:

a. It helps to incentivize users to utilize network resources and increases operator’s revenue.
b. By incentivizing the users, the network will have just enough number of users to occupy the provisioned capacity of the network most of the time, thereby keeping call blocking and call dropping rate and probability within the acceptable levels set by regulatory bodies.

In this present era of converging world of networks, the line of demarcation between mobile networks and the internet is fast fading. Innovation and price still remain the major market movers and will remain a major focus for any provider that anticipates growth and maintaining technological lead.

2.10 Challenges of Users’ Heterogeneity on Dynamic Pricing Schemes

Heterogeneity of users can be viewed in different perspective, in this context, looking at users’ heterogeneity in terms of demographics is the focus. Firstly, in terms of income status, users of the network have different income and budget, therefore the request for services will differ. Wealthy users will not border about the price of the network, because they can afford any price at any given time, while low-income earners may not be able to make call request at some price levels. An operator inclined towards only one of these categories of users will create what is termed the ‘tragedy of the commons’ in economics theory [18], as mentioned earlier. Tragedy of the commons is a situation where a market favours only a class of income or budget. Fairness of the network is measured by how much an operator is able to price the network service to consider a reasonable range of users regardless of their income.

On another note, users’ heterogeneity may be classified with respect to educational status. In rural areas, users may demand for voice call services than data services whereas in the cities and institutions, users may pay higher for data services for educational or administrative purposes. Therefore, an operator should have sufficient information about the users while allocating prices, due to the inherent heterogeneity of users in term of demographics. Challenges due to users' willingness to pay and operators' revenue, and call rate (cost) composition are briefly discussed in the next subsections.

2.10.1 Users' Willingness to Pay (WTP) and Operators' Revenue

Several methods of obtaining Willingness to Pay (WTP) data are explained in literature, with inherent flaws and advantages. Willingness to pay estimation helps to determine a suitable price for the enhancement of revenue on any given good or service.

The approach adopted for obtaining WTP in this research is the revealed preference obtained from market data. Revealed preference based on historical market data presents generally reliable results. Other methods of obtaining WTP such as the use of surveys will be tedious and often limited in the HWN scenario considered, because real purchasing behaviour may not translate into accurate valuations recorded in the surveys by subscribers. Figure 2.9 gives the classification of the different methods for measuring WTP [24].

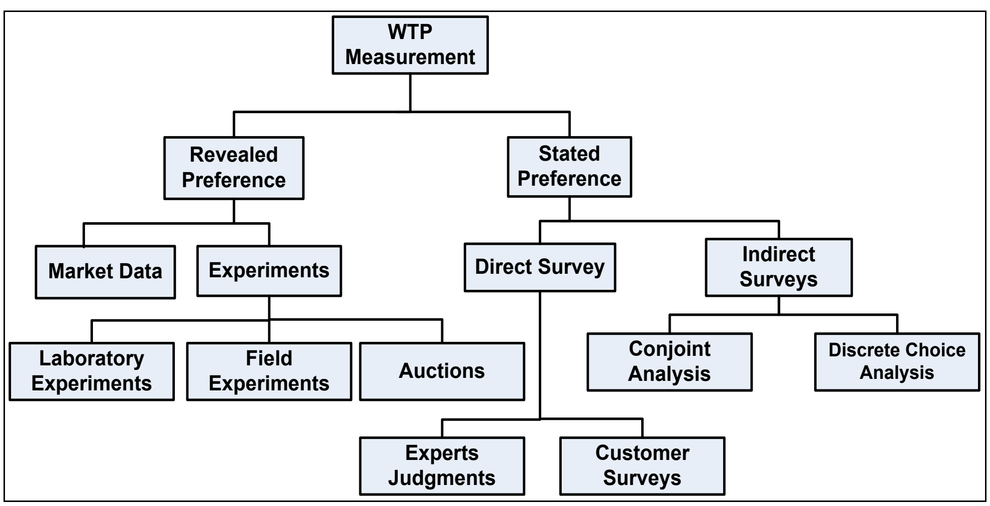

Figure 2-13: Methods of measuring WTP

Figure 2.13 shows the classification of methods used for measuring WTP. Revealed preference, obtained from historical market data of subscribers' response to congestion price updates will enable operators to know the true valuation of services on the network. Revealed preference studies the past action of individuals, and can give current market equilibrium [25]. On the other hand, WTP values can vary with geographical location and individual budget. Some areas may have high WTP than others, thereby creating better opportunity for the providers to maximize profit. Therefore, the service providers' knowledge of users' WTP can enhance their revenue.

Modelling WTP in this scenario will be dependent on the historical responses of users to previously broadcasted or updated service price. Results that are more accurate are obtained because this will reveal the true preference of users during congestion periods. It is worth noting that, obtaining WTP through surveys may be inappropriate, because of users' heterogeneity and diverse user preferences. Furthermore, if users document how much they truly value a service on a survey, it does not directly translate into real purchasing power or behaviour. The WTP differs according to users' importance attached to the class of service demanded. While some users can pay high amount for voice calls, others will rather pay higher for data services. At this point, it was observed that there is need for the network to be able to make appropriate and intelligent adjustments to an uncertain and dynamic network environment.

The effect of users' willingness to pay on call rates has not received much attention recently. The features of an oligopolistic market can describe the telecommunications market. An oligopolistic market describes a scenario where few sellers sell to many buyers. The sellers here represent the network operators while buyers are the users. This creates a competitive platform between operators where the operator that offer more affordable prices have more users. An intelligent marketing strategy for an operator will be to consider what users perceive about rate of calls in comparison to their competitors. Price sensitivity plays an important role in the revenue maximization of operators. Users' willingness to pay can be inferred from price sensitivity function (PSF).

2.10.2 Call Rate (cost) Composition

The rate charged by an operator for any call request is aimed at covering the cost of making the network available and running. The expenses of providing a telecommunication service can be broadly classified into capital costs and operating expenses. The capital cost includes all cost incurred in building telecommunication sites and installing them with equipment and the operating cost include staff salaries, maintenance cost on equipment and the power consumed. The term 'always connected' has cost implications which have to be covered by the users of the network.

The call cost composition for this research can be summarized in the following three points; call termination rate, license fees/renewal and maintenance cost.

a. **Call termination rate:** this is the rate charged by a telecommunication operators for terminating another operators' call on its network. The rate may differ between two operators due to regulatory body's involvement. It forms part of the cost of providing access to a subscriber. There are three models for charging this tariff [26], they are; call party pays (CPP), bill and keep (BAK, peering), and receiving party pays (RPP). Therefore termination rates form part of the call rate composition.

b. **License fees/renewal:** licensing fees are fees paid to regulatory bodies that issue frequency spectrum to operators. The frequency spectrum is leased to the operator, in many cases over a period of time, after which a renewal is mandatory. Regulatory bodies reserve the right to duration, term and conditions of any frequency spectrum license. The lease is usually paid for by the operators, therefore operators need to cover up this cost as well.

c. **Maintenance cost:** this includes, but not limited to cost of keeping the telecommunication equipment functional, staff payments, and so on.

The highlighted call cost may differ significantly within operators due to adoption of different pricing schemes that result in different user response. As a result operators do not have an even profit or revenue maximization. Therefore operators should be sensitive to users' response to service price in order to maximize their profits.

2.11 Related Works on Congestion Control in HWN

In literature, some authors have considered integrating pricing scheme into the CRRM to enhance the efficient utilization of radio resources. Others have focused on using dynamic pricing approach to control congestion. Congestion in the network can be minimized by introducing an incentive to ensure that users limit their consumption of radio resources. The price in this context is the incentive that will be determined by the prevailing network load.

In [8], B. Al-Manthari *et al* propose a call admission control-based dynamic pricing scheme that aims at preventing congestion and maximizing the utilization of resources in wireless access systems. The price algorithm dynamically compute the price of units of bandwidth, forcing actual number of connection to optimal ones based on network load only, with little consideration on users' preference.

In [27], Feng Chen *et al* presents a 'contract binded call admission control' (CBCAC) pricing scheme, which calculates the optimal arrival rates and limits the number of calls admitted. The pricing scheme adjusts price of connection only at high utilization levels. However, it is worthwhile to ensure the network is able to encourage users to make calls also at low utilization levels. The price algorithm can be improved upon to make price adjustments at any utilization level of the network.

Scheme [28], R. Piqueras *et al* propose a dynamic pricing for decentralized RAT selection in heterogeneous scenario. They suggest that whenever the load in one RAT exceeds certain threshold, another substitutive RAT is made more attractive to users by means of the offered price. The price algorithm did not consider incentivising users to make calls at low utilization levels.

From the foregoing literature, the collaborative mechanism, which presents social fairness and promising efficient network utilization, by the integrating the users' and operators' preferences, has not gotten much attention in the research community. This research focuses on extrinsic control of congestion, which is based on efficiently incentivising end users to limit or increase their consumption of radio resources. This is possible due to the sensitivity of users to price changes. This method of controlling congestion reduces cost and enables providers to generate higher revenues.

Pricing the network has a direct effect on users, therefore there is the need to examine the behaviour models of network users, which may yield different user response and price sensitivity. Table 2.3 shows the literature reviewed with the user behaviour model adopted. The table highlights the two major user behaviour models commonly used in literature when examining users' response to price.

Table 2-3: Reviewed literature on pricing, user behavior model and pricing scheme adopted

Reviewed Literature	User behaviour model	Pricing scheme
Mehrdad Manaffar *et al*	Utility function	Priority
Wei Wang *et al*	-	Dynamic
Bader Al-Manthari *et al*	Demand function	Dynamic
Feng Chen *et al* (CBCAC)	Demand function	Dynamic
Sarah Kabahuma *et al*	Utility function	Dynamic
Roberto Battiti *et al*	Utility function	Dynamic

Roger Piqueras *et al*	Utility/Demand	Dynamic (RAT)

Roger Piqueras *et al* in [28], explains the two basic models to be considered when including pricing concepts in RAT selection problems, which are utility model. Utility models define utility functions, and a usage-based pricing model, which explains the application of pricing model to the RAT selection in HWN scenario. Users' behaviour model can be examined by either utility function or demand function, for this research, we adopt the utility function as users utilize the radio resource. Utility function relates to the maximum price a user is willing to pay for using the radio resources or for a specified QoS.

The contributions of this work are to employ a collaborative dynamic pricing approach that dynamically prices the HWN, driving its utilization to a goal state through price incentives. Furthermore, using Q-learning method illustrate how the price entity can reach an optimal price policy at every utilization state of the HWN by adopting a 'reward-driven' price policy. Consequently, controlling congestion and enhancing both users' and operators' utilities in a Heterogeneous Wireless Network.

2.12 CHAPTER SUMMARY

This chapter presented an overview of HWN and radio resource management schemes in NGWNs. The collaborative decision making which is the focus of this research was then explained in view of the global vision of radio resource management. The reinforcement learning algorithm was explained with reasons for choosing the Q-learning techniques among others. Highlights of congestion issue and methods of controlling congestion in HWN in the literature was presented. Pricing schemes were also investigated and emphasis was placed on the control of congestion using dynamic pricing. The challenges of users' heterogeneity on dynamic pricing scheme and the effect of users' willingness to pay on operators' revenue was equally examined. This chapter then concluded by presenting the shortcomings of related works and then highlighting the contribution of this research.

3 PROPOSED SCHEME AND ANALYSIS

This chapter gives details of the proposed scheme for addressing congestion problems in HWN.

Subscribers respond to price changes based on different levels of willingness to pay (WTP) for services offered by operators. The operators' knowledge of users' demographics will enhance the proper price adjustments to obtain the optimal price of services. The objective of the proposed dynamic pricing scheme is in two folds, firstly to control congestion in the HWN and secondly to enhance both users' and operators' utility in the HWN. Figure 3.1 below gives a summary of the objectives of the proposed collaborative dynamic pricing scheme (CDPS).

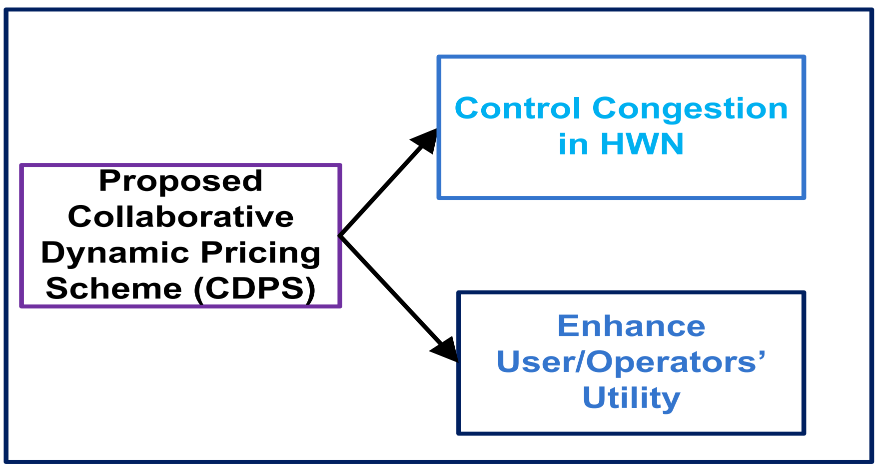

Figure 3-1: Function of proposed collaborative pricing scheme

3.1 Heterogeneous Wireless Network Model

Consider a heterogeneous wireless network consisting of a number of RAT whose radio resources are jointly managed. The individual RATs making up the heterogeneous network support multiple services such as voice, video, data and so on. The percentage demand of the radio resources determines the utilization condition of the network. The state space of the HWN comprises of the total participating RAT and services available on the RATs.

Let *m* denote the total number of RATs, and *k* the total number of services, the state space is denoted by vector z, can be written as follows [5]:

$$z = \{p_{ij}, q_{ij}, : i = 1,..m, j = 1,..k\} \quad (3.1)$$

p_{ij} is the number of ongoing new calls and q_{ij} is ongoing handoff calls, in RAT-*i* with service class-*j* respectively. We also adopt the bandwidth reservation policy described in [5] which prioritize handoff calls, by reserving a portion of bandwidth for handoff calls. Therefore, new calls will be rejected upon reaching a certain threshold. The threshold for new calls in RAT-i is denoted as T_p and the threshold for handoff calls in RAT-i is denoted as T_q. Let the total capacity of the HWN be the summation of the individual RATs capacity, expressed as follows;

$$C_1 + C_2 + ... + C_m = C_{mk} \quad (3.2)$$

Expressing the admissible state, Ω_A in the HWN (that will ensure non-violation of QoS requirement of ongoing calls and reservation policy of handoff calls) is given as follows:

$$\Omega_A = \left\{ z \,|\, \sum_{j=1}^{k} b_j(p_{ij}) \leq T_p \;\forall i \;\wedge\; b_j(q_{ij}) \leq T_q \;\forall i \;\wedge\; \sum_{j=1}^{k} b_j(p_{ij} + q_{ij}) \leq C_i \;\forall i \right\} \quad (3.3)$$

b_j is the basic bandwidth unit, (bbu) needed to make a call of service class-j. The basic bandwidth unit (bbu) of each class of service differs; that is, in the network, classes of ongoing calls may have different bandwidth. When the sum of the bbu of the class of service in the network equals the total capacity of the network, then incoming calls (either new or handoff calls) will be denied access. In addition, if none of the RATs have enough bbu to accommodate the requested class of call, then the call is blocked. An operator ensures that blocking or dropping probabilities are at acceptable levels.

3.2 Heterogeneous Wireless Network Utilization States

Four network utilization states, based on demand for service are considered for this research, they are underutilization state (S_1), fairly utilized state (S_2), goal state (S_3) and congestion state (S_4). The 'states' show the level of demand on the total capacity, C_{mk} of the HWN, therefore, the following equations describe the network utilization states;

$$S_1 = (a \leq dS_1 \leq b) \quad (3.4)$$

$$S_2 = (c \le dS_2 \le d) \tag{3.5}$$

$$S_3 = (e \le dS_3 \le f) \tag{3.6}$$

$$S_4 = (g \le dS_4 \le h) \tag{3.7}$$

Where ‘a’, ’b’, ‘c’, ‘d’, ‘e’, ‘f’, and ‘h’ are demarcations on demand levels, which can assume fixed percentage values of the total capacity. The demand level in a given state, S is denoted as ‘dS’. The equation (3.4) represents the underutilized state where demand is very low, equation (3.5) describes the radio resources is fairly utilized, equation (3.6) represents the goal state utilization and (3.7) represents the network congestion state, where prices are highest.

3.3 Model of Users’ Willingness to Pay

In [29] the widely used Weibull-distribution was employed to model WTP values, with mean exponential demand function and shape. In this research we employ the demand function as used in [30] which is a special case of Weibull distribution, given as follows:

$$W_{(t)} = e^{-(\frac{p_{(t)}}{p_{(0)}}-1)^2} \tag{3.8}$$

Where $P_{(t)}$ is the price of access at time t, and $P_{(0)}$ is the previously observed price. $W_{(t)}$ indicates the percentage of users that are willing to pay for the new price at time t. Furthermore, the WTP values will vary based on the different prices of service charged at different utilization levels.

The scheme in [8] set price that ensure users have sufficient WTP according to the demand model used. In this research, the price of services at different utilization levels are therefore assumed on a rating scale so as to have 95%, 85%, 65% and 25% of users having sufficient WTP when utilization level is at S_1, S_2, S_3 and S_4 respectively [12].

3.4 Flowchart diagram for the Proposed Dynamic Pricing Scheme

The procedure of the proposed dynamic pricing scheme for a HWN is illustrated in Figure 3.2 in this section. A feedback loop is introduced for price evaluation which incorporates users' WTP factor in evaluating service price. Figure 3.2 explains the sequence of operation of the proposed scheme aimed at enhancing the efficiency of RRM in HWN as explained earlier.

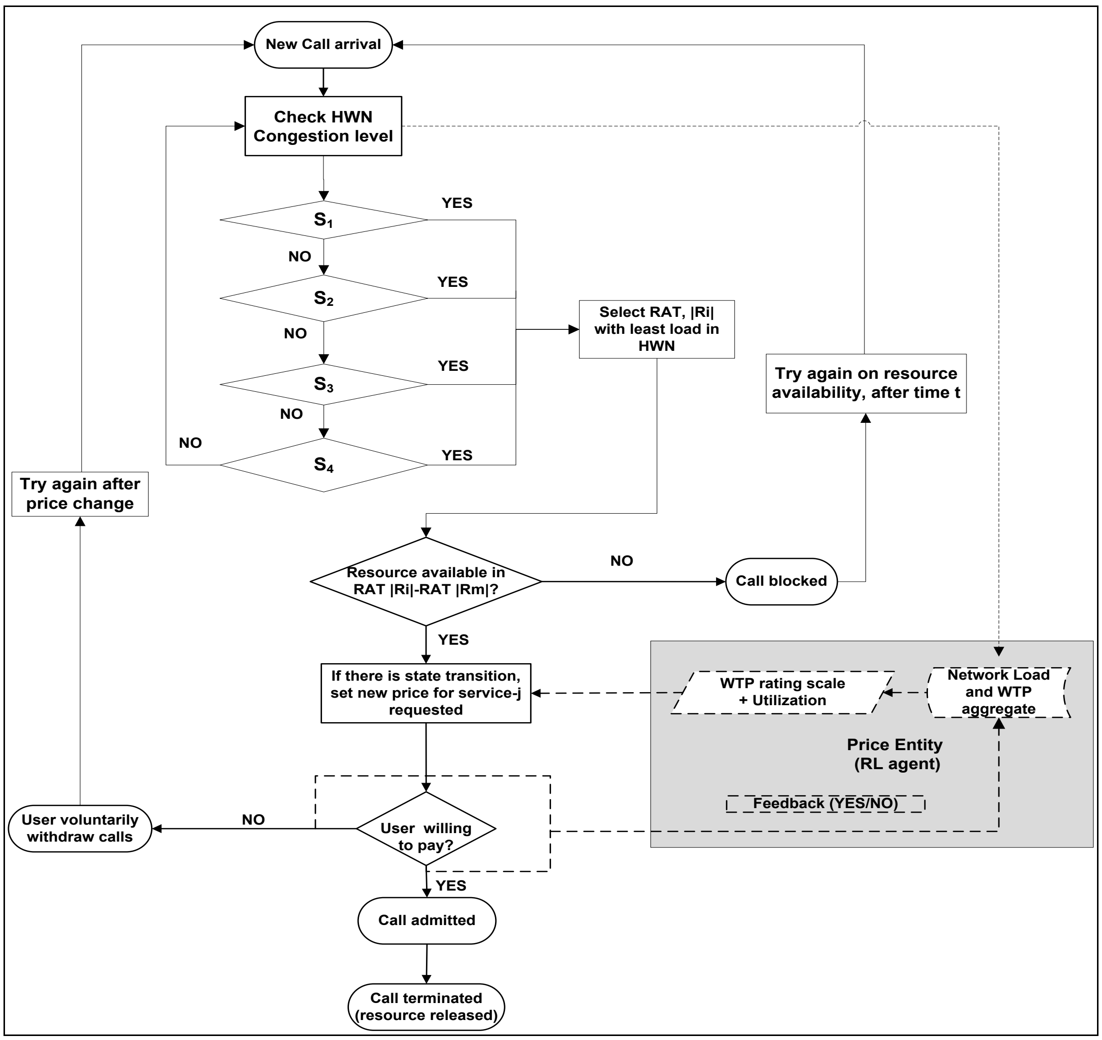

Figure 3-2: Proposed scheme for HWN

As shown in Figure 3.2 the proposed scheme consists of Resource (information) monitoring, Decision making and Decision Enforcement [6]. The fundamental basis for global vision of resource management is optimization, which can be achieved through the intelligent feedback system analysis. The proposed scheme introduces this feedback by monitoring the response of users as the price of service changes. This yields the aggregate WTP which is then incorporated for the service price evaluation. Therefore, the price of access is evaluated not based on network utilization only, but also on WTP of users. Consequently, the network is able to make improved price adjustments from the inputs obtained and the optimal price of service that is achieved enhances both users' utility and providers' revenue.

Users are price sensitive, therefore the service price of a network will determine users' preference among competing service providers. Users' willingness to pay is also affected when users perceive that one service provider enhances their utility than the other. Consequently, the provider that gives cognizance to users' willingness to pay will achieve an enhancement of revenue. Users will pay for a service only if the price of the service enhances their utility and will not pay otherwise. Therefore, a provider should ensure an economically efficient network that incorporates users' WTP when evaluating the network congestion price.

3.4.1 RAT Selection Algorithm for HWN

The proposed scheme incorporates RAT selection algorithm, which checks congestion level based on percentage demand (utilization) and the state of the HWN before proceeding to evaluate service price. The flowchart in Figure 3.2 elaborates the RAT selection algorithm and verification of the utilization levels in the HWN. The network utilization levels are calibrated into different percentage demand on the total capacity of the HWN. RAT preference in HWN is based on least loaded RAT, i.e. the least loaded RAT is selected first [31].

The price entity evaluates the service price of the class of call requested based on utilization and WTP value of users. The RL algorithm uses the reward values of each state to estimate the optimal price policy. The WTP values are adjusted for price to be within maximum price (pmax) and minimum price (pmin). The next section explains the proposed RL analysis for the HWN.

3.5 Reinforcement Learning Analysis for a HWN

Reinforcement learning is a process of acquiring information and making improved decisions about the states and actions in a 'system'. In this dissertation the system corresponds to a heterogeneous wireless network. The acquired information is used to improve on the system's response which is aimed at achieving an optimal reward value based on past experience. The learning process involves learning through experience and in the process learning actions that yield the highest desired reward over time. Apparently, the actions do not only affect the immediate reward but the total collective reward, which is a cumulative of each reward being considered as the action process iterates. One of the major features of the reinforcement learning is that it explicitly considers the whole problem of a goal-directed agent interacting with an uncertain environment [32]. Figure 3.3 shows an illustration of a basic reinforcement learning process.

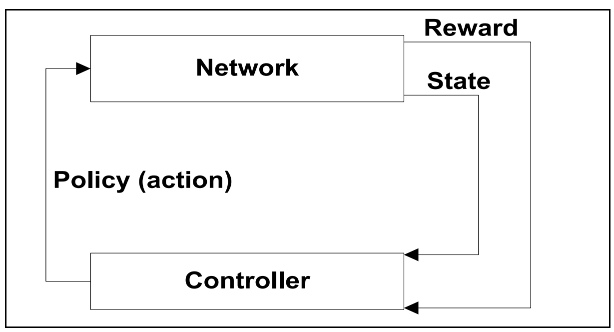

Figure 3-3: Basic Reinforcement Learning illustration

The *'agent'* (or decision maker, used interchangeably) hereafter refers to the price entity that executes the price policy decisions. The network state is controlled by the action taken by the agent and the reward obtained is fed back into the system for proper optimal adjustments. The Markov decision process (MDP) helps to further give clarity on the implementation of the reinforcement learning process.

3.5.1 Markov Decision Processes (MDPs) Analysis

MDPs are a way to model sequential decision making under uncertain or dynamic environments. To effectively implement the reinforcement learning into the HWN, the network needs to be modelled using a MDP. The purpose of employing a MDP is to find a policy for the decision maker. The decision maker will be able to make optimized decision regarding network utilization and WTP values of users for the purpose of enhancing users' and operators' utility. The objective of the MDP is to find a policy that maps states to the set of actions that will optimize the network utilization. This is achieved by maximizing expected rewards or minimizing costs associated with the network.

Preliminaries for MDP are defined as follows as given in [33];

- MDP can be represented by a tuple- $\{S, A, R, P\}$, where S and A denotes a finite set of states and actions respectively.
- $P : S \times A \times S \rightarrow [0, 1]$, denotes the transition function
- P (s, a, s') gives the probability of reaching state s' after executing action a when initially in state, s.
- R: $S \times A \times S$ is the reward function, R (s, a, s') gives the immediate reward for the transition (s, a, s')

Real world environments are usually non-deterministic in nature. Therefore the transition function can take a state, s as input, action, a and a next state, s' and give a feedback of the probability of reaching the next state after taking the action, a. The Markov environment is one which is non-deterministic. Historical occurrence may affect the outcome of future states. Therefore, a non-deterministic environment such as the telecommunications resource utilization can be described by a Markov environment. Transition of states is based on historical utilization of radio resources and price: i.e. the probability of reaching a state may be based on the previous states reached. For this research four different radio resource utilization states - $[S_1, S_2, S_3, S_4]$, are considered, where S_3 is our *'goal state'*. Figure 3.4 shows the parameters relevant to modelling an MDP. The MDP takes the following model [32][34]:

S: a set of states
A: a set of actions
T(s, a, s'):probabilistic transition model
C (s, a, s'): cost model
R: reward model
G: set of goals
S_0: start state
γ : learning parameter
α: discount factor

Figure 3-4: MDP evaluation parameters

The models and factors to be considered in a MDP are explained as follows:

- States (s): The states represent the current/present state (s), of the HWN, can be congested or underutilized. Each state has an associated reward.
- Actions (A): The set of actions are the set of executable decisions in any present state (s), which if taken, will result in a next state (s') or remain in the previous state.
- Transition model (T(s, a, s'))The transition model has a Markov characteristics which is probabilistic. Transition to another future state (or next state) is only dependent on current state and not past states. Transition occurs in an event of call arrival or departure that leads to a change of state.
- Cost model (C (s, a, s'))The cost model is also has a Markov characteristic, in that each state has a unique associated cost.
- Reward model (R): In this work, reward is defined as the 'utility benefit' derived for being in a state, for both users and operators. The total utility is the sum of users' utility and operators' utility. Therefore, the reward for each state changes as the utilization level changes.

- Goals: The outlined goals in this research is to obtain action and states that yields reward that will enhance both users' and operators' utility. The 'goal state' is therefore the state that achieves the maximum reward for both user and operator.

- Start state: The start state refers to the state of the network the MDP begins with.

- Learning parameter (γ): The learning parameter explains how fast or slow a reward is considered and chosen as the best for the current state. Its value usually lies within 0 and 1 ($0 \leq \gamma < 1$).

- Discount factor (α): Finite horizon problems of this nature will employ discount factors to keep total reward and costs of the network finite. It also ensures that a higher present reward is better to be chosen immediately, than an uncertain future reward which is envisaged to be higher.

Given a set of optimal criterion, the goal of decision making is to find an optimal behavior to suit the criterion. Under this set of optimal criterion it is pertinent in this work to find a policy that maximizes the expected total reward value.

3.5.2 Q-Learning Model and Analysis for the Proposed Pricing Scheme

As highlighted earlier, Q-Learning is a form of Reinforcement Learning (RL) that combines learning and execution concurrently. It works as follows [34];

- An estimated value called Q-value is assigned to each state.

- On visiting a state, a reward is obtained which is used to update the estimate of that state.

- Iterative visit of states is done because rewards obtained might be stochastic.

- Q-value can be written as [35]

$$Q(s,a) \leftarrow Q(s,a) + \alpha(r + \gamma.\max a\, Q(S', a)) \qquad (3.9)$$

Learning process can take time because of the possibility of choosing wrong actions that yield low rewards (some literature refer to low rewards as 'punishments'). Early stage of learning is important for exploring the outcome of unknown actions, due to the uncertainty of the environment. On the other hand, any error made early will enable the network learn the best reward in ample time, and continue to make better decisions onwards.

To employ the Q-learning algorithm, total system states (S), actions (A) and associated reward (R) for the HWN are explained and modelled as follows;

a. States: The call requests/arrival (demand) can be used to describe the utilization level or the load in the HWN. As stated initially, we have four utilization states $(s \in S)$, determined by the arrival and departure of calls resulting from a price update event.

b. Actions: When a call arrives, a given action is executed based on inputs obtained from the current state of the network. The actions that can be taken are represented in numerical values [36]. The values 0 means reject the call (a_1); 1 means accept the call and adjust service price (a_2); 2 accept the call without price adjustment (a_3); 3 departure of a call with price adjustment (a_4); 4 means departure of a call without price adjustment (a_5). The action space, A_Φ is given as;

$$A_\Phi = [a_1, a_2, a_3, a_4, a_5] \tag{3.10}$$

The total executable actions, A_s in the four possible states in the HWN are given as follows;

$$\begin{aligned} A_1 &= [a_2, a_{3,} a_5] \\ A_2 &= [a_2, a_3, a_4, a_5] \\ A_3 &= [a_2, a_3, a_4, a_5] \\ A_4 &= [a_1, a_3, a_4, a_5] \end{aligned}$$

An adjustment in service prices, that is actions a_2 and a_4, only occurs when the state of utilization changes. The prices of service are not adjusted when utilization is still within a specific state (actions a_3 and a_5). Calls are assumed to be rejected only when resources are not available (action a_1- call rejection), which is possible at S_4.

c. Rewards: The rewards are the collaborated utility benefit achieved for both users and operator in a given state. In some literature, Willingness to pay (WTP) is used interchangeably with utility benefit. Reward values can be generated based on used bandwidth, arrival rates, call holding time and access price. Reward values are computed based on the percentage utility benefit obtained in each utilization state.

From the foregoing, a transition from a state s to s' occurs in an event of call arrival or departure due to previous or recent action taken. The state-action pair gives an associated reward value, obtained based on WTP and network utilization, as shown in the flowchart. Furthermore, at every state-action pair, there is a dynamic price update event. An episode refers to a call arrival or departure and a price update event. The Q-learning therefore enables the price entity to learn the behaviour of the system as the episodes continues for a given duration, for example 24 hours period.

For illustration purposes, ten state scenarios are given in Table 3.1:

Table 3-1: State transition example and price update event

State transition scenario	Possible action(s)	Dynamic Price update	Associated reward
S_1-S_1	a_2, a_3,a_5	Ps_1	R_1
S_1-S_2	a_2	$Ps_1+\Delta P$	R_2
S_2-S_1	a_4	$Ps_2-\Delta P$	R_3
S_2-S_2	a_2, a_3,a_4,a_5	Ps_2	R_4
S_2-S_3	a_2	$Ps_2+\Delta P$	R_5

S_3-S_2	a_4	Ps_3-ΔP	R_6
S_3-S_3	a_2,a_3,a_4,a_5	Ps_3	R_7
S_3-S_4	a_2	Ps_3+ΔP	R_8
S_4-S_3	a_4	Ps_4-ΔP	R_9
S_4-S_4	a_1,a_3,a_4,a_5	Ps_4	R_{10}

From table 3.1 the price of service in a given state (Ps_1, Ps_2, Ps_3, and Ps_4), changes dynamically based on utilization and WTP values (within pmin and pmax). The price 'ΔP' is the unit change in price that is added or subtracted when there is a transition from one state to another new state.

To solve the problem of uncertainty with respect to the state and action pair leading to a goal state from a start state, a 'reward-driven' price policy needs to be formulated. The policy is the set of outlined rules on how the pricing entity should evaluate price based on utility benefits. The policy ensures that actions that maximizes utility are taken at each state, leading to the goal state. The total reward, TR from a policy can then be formulated as [34]:

$$TR_{(s)} = EU\left(\sum_{s=1}^{4} \gamma R_{(s)} \mid \pi\right) \tag{3.11}$$

It states that the reward from a policy, π is the sum of the discounted expected utility, EU of each state visited by that policy. The optimal policy is then the policy that maximizes this equation. The total users' utility benefit (reward) is measured in terms of the percentage of users willing to pay the updated price at each utilization state ($WTP_{(S)}$), based on a rating scale. Operators' utility is evaluated in terms of network utilization, ($REV_{(S)}$). The expected reward for this research is therefore evaluated with the following equation:

$$R_{(s)} = WTP_{(s)} + REV_{(s)} \tag{3.12}$$

Therefore, for each state of the network, total reward (TR) is computed as follows:

$$TR_{(s)} = \gamma (WTP_{(S)} + REV_{(S)}) \forall s \tag{3.13}$$

3.6 Performance Metrics Considered

Performance metrics are quantities used to evaluate the efficiency of a proposed mechanism. The performance metrics chosen for this research are new call blocking probability, handoff call dropping probability, provider's utility, users' utility, and network utilization. The performance metrics are presented in the following subsections.

3.6.1 New Call Blocking and Call Dropping Probabilities

New call blocking and handoff call dropping are measures of determining congestion in the network. New call blocking probability and handoff call dropping probability increase as the network load increases and vice-versa. During high congestion levels, new calls will not be admitted into the network because of limited network resources. Likewise, if the reserved bandwidth for the handoff call is exceeded, subsequent handoff calls will be dropped. The ongoing calls are the call requests that are currently utilizing radio resources. The ongoing calls, both handoff and newly accepted calls determine the current network load condition. As different service class of calls with different basic bandwidth units (bbu) gets admitted into the network, the probability of accepting a new call or handoff call request reduces gradually, until a call request is blocked or dropped.

The scheme in [5] employed the steady state solution of the Markov model to obtain new call blocking and handoff call dropping probabilities. Traffic intensity of new calls and handoff calls is given as $\rho_{pij} = \frac{\lambda_{pij}}{\mu_j}$, $\rho_{qij} = \frac{\lambda_{qij}}{\mu_j}$ respectively. The steady state probability is given as:

$$P_z = \frac{1}{T} \prod_{i=1}^{m} \prod_{j=1}^{k} \frac{(\rho_{pij})^{p_{ij}}}{p_{ij}!} \frac{(\rho_{qij})^{q_{ij}}}{q_{ij}!} \quad z \in \Omega_A \tag{3.14}$$

Where T is the normalization constant given by:

$$T = \sum_{z \in \Omega_A} \prod_{i=1}^{m} \prod_{j=1}^{k} \frac{(\rho_{pj})^{p_{ij}}}{p_{ij}!} \frac{(\rho_{qj})^{q_{ij}}}{q_{ij}!} \tag{3.15}$$

Hence, the probability of accepting a new call or handoff call into a HWN is determined by the availability of resources. The set of states for which new class-j call is blocked in a group of collocated cell is given as [5, 22]:

$$\Omega_b = \left\{ z \in \Omega_A \,|\, \sum_{j=1}^{k} b_j + (b_j\,(p_{ij} + q_{ij})) > C_m \;\forall i \vee \sum_{j=1}^{k} b_j + (b_j \times p_{ij}) > T_p \;\forall i \right\} \tag{3.16}$$

The set of states for which handoff class-j call is dropped in a group of collocated cell is given as:

$$\Omega_d = \left\{ z \in \Omega_A \,|\, \sum_{j=1}^{k} b_j + (b_j\,(p_{ij} + q_{ij})) > C_m \;\forall i \vee \sum_{j=1}^{k} b_j + (b_j \times q_{ij}) > T_q \;\forall i \right\} \tag{3.17}$$

Let PB_{pij} and PD_{qij} represent new call blocking probability and handoff call dropping probability respectively in the HWN. Therefore, new call and handoff call probability is computed as [5]:

$$PB_{pij} = \sum_{z \in \Omega_A} P_z \tag{3.18}$$

$$PD_{qij} = \sum_{z \in \Omega_A} P_z \tag{3.19}$$

Considering the focus of this research, the relevant metric to this study is the new call blocking probability and handoff call dropping probability. However, in a pricing scheme scenario, handoff calls are only charged at point of admission, therefore handoff calls are not affected by congestion prices since they have been charged from the cell where the call was initiated [21]. Nonetheless, handoff calls remain relevant to the utilization or load level of the HWN under consideration.

3.6.2 Network Utilization- Arrival and Departure Rate

Controlling the network utilization for optimum benefit is a major focus. The utilization of the network involves the regulation of demand for radio resources and the end benefit afterwards. The increase in the network resource utilization, for increasing cost benefits, is economically driven. The actual usage of network or class of service demanded is not easily predictable or controllable. The variation in demand over time and space is also a major factor that creates ever-changing parameters to be considered in obtaining the actual reasons for the network utilization obtained or envisaged [37].

Efficient network utilization is crucial to network operators who envisage a good return on investment. Inefficient network utilization may lead to over provisioning of radio resources that provide unnecessary increase in the cost incurred by operators.

The methods adopted to regulate the usage of radio resources can lead to either a decline or improvement of utilities of both the users and operators. Utilization in terms of arrival and departure rate will enable operators to observe the performance of the dynamic pricing scheme. Therefore, network utilization is an important metric to evaluate the performance of the proposed collaborative dynamic pricing scheme.

3.6.3 Providers' Revenue and Users' Utility Evaluation

Due to an evolving and unpredictable telecommunication market, all operators continue to engage in the price and innovation battle, as they envisage high profit and reduction in operational cost. The number of loyal subscribers have a major effect on the profit of operators. Therefore, it is important to ensure that the users are offered services and price that enhance their QoS and monetary utilities. This will enable achievement of more loyal subscribers as a result profit is enhanced. Operators' knowledge of users' monetary value (WTP) attached to same services offered by their competitors is of paramount importance in setting service price. In addition, information of user's response to network price as the load changes can be obtained by historically observing the network usage and users revealed preference, apparently the operators can intelligently set service prices for an improved network utilization and profit enhancement.

Operators do have an expected target of revenue and profit envisaged for every fiscal and operation year. The expected revenue is dependent on the number of successful calls admitted and the duration of each calls or data volume consumed by subscribers. In chapter two of this work, the call rate (cost) composition was explained to give a general overview of the type of cost incurred by operators. The expected number of connection, E_{kj} in the system is a product of traffic intensity and acceptance probability, P_{Aj}, given as in [38].

$$E_{kj} = \rho_{ij} (P_{Aj}) \forall i \tag{3.20}$$

Hence, total number of connections for class-j service, E_{Tj} is computed as follows:

$$E_{Tj} = \rho_{pij}(1 - PB_{ij}) + \rho_{qij}(1 - PD_{ij}) . \tag{3.21}$$

Therefore, the expected revenue R_{Ej} is the product of the total number of connections E_{Tj} and unit price per bandwidth (or per second billing) for the class-j service and the number of subscribers making connections [38, 39]. Let N_j be a non-negative integer, which is the number of subscribers having sufficient WTP at any given time. Therefore, expected revenue is computed as follows:

$$R_{Ej} = E_{Tj} \times p_j \times N_j \tag{3.22}$$

Users as well as operators envisage social fairness as the radio resources is utilized, this poses a social welfare optimization situation. In [40], social welfare was defined as the sum of users' and providers' utility in the system. Selfishness of user or provider does not lead to a socially efficient situation.

Users derive their utility benefit (reward) from their individual WTP values for the services requested. WTP values differ with users' demographics and worth placed on the service requested. Users will therefore have varying WTP for same services requested. Users' monetary and QoS utility are a measure of users satisfaction or preference. Deriving from [41], the users' QoS utility (U_{Qi}) is measured in terms of the new call blocking probability and hand off call probabilities of class of service requested and users' monetary utility (U_{Mj}) is derived from [12]. The users' QoS and monetary utility is therefore computed in this research as follows:

$$U_{Qj} = \sum_{j=1}^{k} \exp - (P_j) \forall i \tag{3.23}$$

Where P_j refers to the QoS metrics that take into account probability of blocking and dropping a class-j call in the HWN. The users' monetary utility in terms of utilization state and WTP values for a given class-j service, is computed as follows:

$$U_{Mj} = \sum_{j=1}^{k} \beta \ln(W_j) + \omega_j \tag{3.24}$$

Where β is the coefficient of the logarithmic constant, which varies with class of service requested and ωj, is a constant for adjusting the offset of U_{Mj} [12]. Therefore, ω_j is varied according to demographics of users and value attached to the requested call.

3.7 CHAPTER SUMMARY

This chapter extensively explained the HWN model and utilization states, presented the proposed design framework and the approach to modelling users' WTP using Weibull distribution. The flowchart of the proposed scheme was presented along with the RAT selection algorithm. The Markov Decision Process (MDP) was used to describe the HWN. The Q-learning technique was employed to model the behaviour of the proposed pricing scheme in response to network utilization and users' response to price changes. Possible states and actions that suit the description of the HWN and yield an improvement on radio resource utilization was developed. This chapter was concluded by presenting the relevant performance metrics such as blocking and dropping probabilities, user and operators' utility.

4 PERFORMANCE EVALUATION OF PROPOSED DYNAMIC PRICING SCHEME

The experimental validation of this research is implemented by numerical simulation using the MATLAB tool. The MATLAB simulation tool was used to evaluate the scenarios of the proposed dynamic pricing schemes. Suitable parameters were carefully chosen to model the HWN scenarios examined.

4.1 Evaluation Framework Overview

MATLAB enables numerical evaluation of experimental ideas and implementation in an easy and comprehensive manner. The block diagram of the proposed framework is given in Figure 4.1.

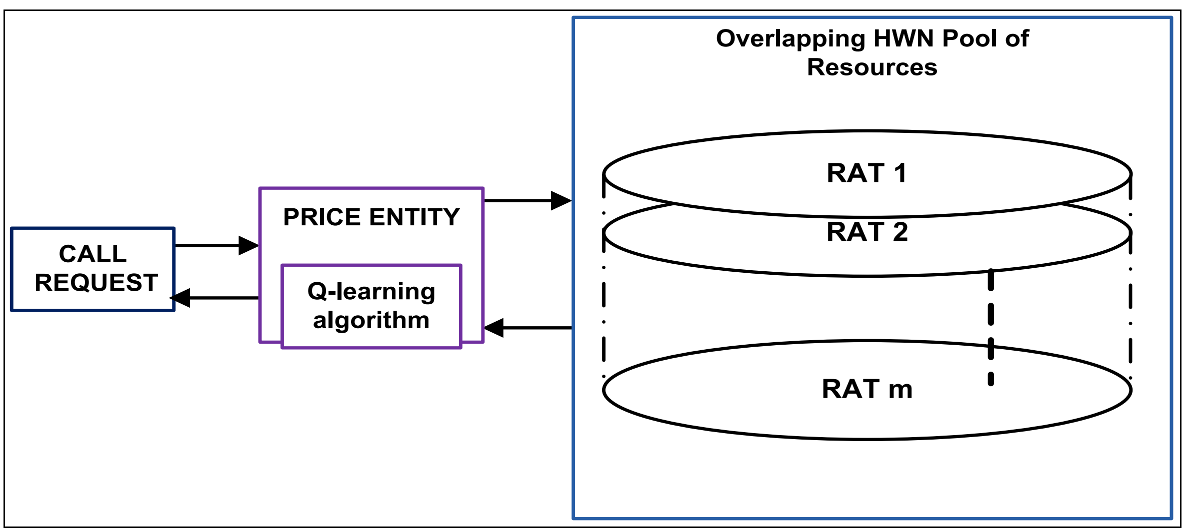

Figure 4-1: Design framework of proposed dynamic pricing scheme

Figure 4.1 shows how a call request to utilize radio resource in the overall pool of HWN goes through the price entity which is integrated with RL algorithm. We assume a fully overlapped coverage of the RATs to save installation cost and improve network performance [5, 42]. The proposed design framework presents an intelligent management of resources using price, for the efficient utilization of radio resources in the HWN pool. The requirements and limitation of the evaluation framework are explained as follows.

4.1.1 Requirements of Evaluation Framework

Requirements for the proposed framework is a database system that keeps record of previous radio resource utilization levels and users' response to price (WTP aggregate). The price entity takes into account that handoff calls are not charged for the variations in price during congestion periods, due to the fact that they have been charged in the initial RAT before handover occurred.

The RL framework requires an iterative exploration mechanism implemented on MATLAB to obtain sequence of events (state-action pair). The objective is to enable the HWN price entity learn an optimal price policy that will incentivize users to increase or reduce request for radio resources depending on the HWN states.

4.1.2 Limitation of Evaluation Framework

The limitation of the proposed framework is that firstly, it is a numerical simulation, which may give room for over estimation of parameters thereby, giving results that are ideal and may not be practicable. However, numerical simulation for the framework provides an overview of the envisaged improvement of the proposed collaborative dynamic pricing scheme in comparison to existing pricing schemes in the control of congestion and enhancement of users' and operators' utilities in HWN. This limitation may be improved upon when implemented on network simulation tools such as the NS2, NS3 and OPNET categories.

4.2 Congestion Price Evaluation of the Proposed Dynamic Pricing Scheme

To evaluate the equilibrium congestion price, there is a consideration of the demand function equation as given in equation (4.1). It is assumed that there exists a price, p which is above or below users' WTP [39]. This price will discourage or encourage just enough users to make connection requests at any period. Demand is a function of price, therefore it determines the arrival rate of the subscribers to the network and call holding time. Arrival rate determined by a demand function is computed as follows [21]:

$$\lambda_{j(t)} = f(P_{j(t)}) = \sigma_{j(t)} e^{-(\theta_{j(t)} P_{j(t)})} \tag{4.1}$$

$\lambda_{j(t)}$ is a Poisson arrival rate of a subscribers into the HWN demanding service-j $(\forall\, j \in k)$. Where $\sigma_{j(t)}$, is the demand shift constant, and $\theta_{j(t)}$, is the price elasticity of demand (the change in demand for a product or service due to change in price) and $P_{j(t)}$ is the price of bandwidth for class-j service requested in that time instance. The equation (4.1) above gives a representation of users' call arrival rate, using a demand function. Due to the variance in the QoS of service classes and different user behaviour, the price elasticity of demand, $\theta_{j(t)}$ and demand shift constant, $\sigma_{j(t)}$ can assume different values at any time of the day [21]. The demand function above takes care of these changes. For this research, the demand shift constant is varied according to the time of the day, utilization and price. Figure 4.2 shows the price sensitivity function of users to price variation, derived from (4.1).

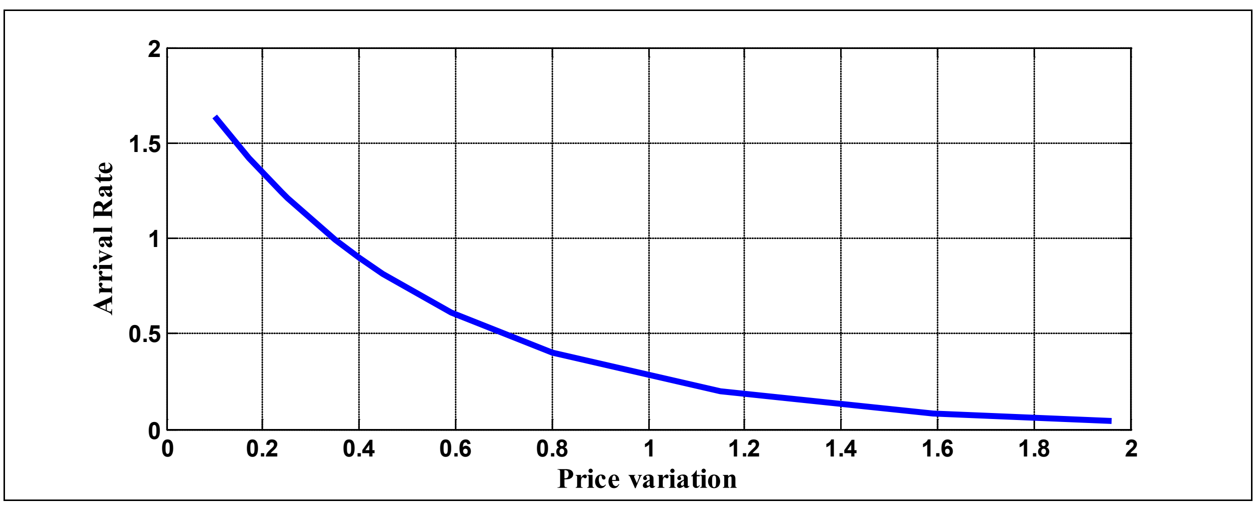

Figure 4-2: Effect of price variation on arrival rate

In order to obtain the equilibrium congestion price of services in a network, (considering both providers' and users' preference), some important measures need to be taken note of. In scheme

[39], the optimal price equation evaluated the price with respect to users and operators' preferences. Examining the operator and the user in terms of price (or utility) preference, the operator will prefer to choose a price of services to enhance revenue per time in the HWN, and on the other hand, the users aim to enhance their QoS utility and monetary utility [12]. Let $\lambda^*(t)$ be the optimal call arrival rate that suits users' WTP and operators' revenue, in a given time. The arrival rate, λ* is obtained by varying the demand shift constant, $\sigma_{j(t)}$ according to the time of the day. It is important to note that users may decide not to make connection request in an event of a price update greater than their maximum WTP, no matter how good the QoS is [12]. The WTP values are also dependent on the service price and the worth a user ascribe to the service requested.

As utilization increases, the price of a service class-j is evaluated as follows:

$$P_{j(t)} = P_{(0)} \pm \Delta p_j \tag{4.2}$$

Where Δp_j is the unit price value added or subtracted, depending on a class-j service, due to utilization level (state) of the network, and $P_{(0)}$ is the previously observed price. By incorporating WTP of users based on class of service, the price of service class-j, with users' WTP incorporation is therefore calculated as follows:

$$P_{wj(t)} = P_{j(t)} \pm W_j \tag{4.3}$$

W_j is the WTP values of Weibull distribution as given in previous chapter.

Some general limitations can be drawn out from the demand model as explained in [43]: the model does not account for users' ability to anticipate future lower price, suitable to maximize their monetary utility. This anticipatory behaviour of users is complex and demand will depend on current network utilization state, advertised price and the changes in price dynamics over time. The demand level and the current price determine the arrival rate, yielding a revenue enhancement strategy.

4.3 Price Policy Evaluation in the HWN

Equilibrium price policy is the price policy that offers the best reward values. As aforementioned, reward is the utility benefit derived for being in a state, for both users and operators. Users' utility refer to QoS utility (guarantee) and monetary utility (price), while operators' utility refers to revenue obtained from radio resource utilization. From the general economic point of view, the total utility is the sum of user and operators' surplus, as shown in the demand and supply curve in Figure 4.3.

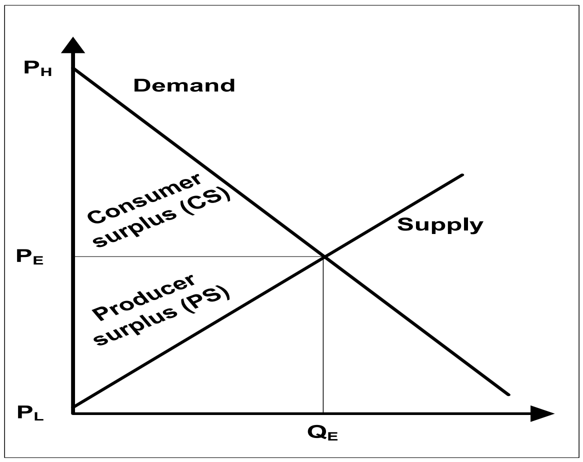

Figure 4-3: Demand and Supply curve

The Total benefit is the sum of user and operators' benefit. The equilibrium price, P_E is the price that enhances the utility of both user and the network operator. Table 4.1 gives an example of user and operator preferences as utilization changes, and the reward values (r_1-r_4). Recall that total reward, $TR_{(s)}$ is the sum of the percentage of users' having sufficient WTP ($WTP_{(s)}$) at each state and the network utilization ($REV_{(s)}$).

Therefore, the targeted choice of state is state 3, where we assume social fairness is adjusted appropriately for both users and operators. At state 3, it can be deduced that users' and operators' utility will be enhanced over time.

Table 4-1: Example of a preference table for users and operators in each state

	User		Operator		
States	***QoS Utility (Increasing order)***	***Monetary Utility (price)***	***Revenue***	***Radio resource utilization***	**Reward Values/state**
S_1	Low	Surplus	Low	Underutilized	r_1
S_2	Medium	Cheap	Average	Moderate	r_2
S_3	***High***	***Affordable***	***Revenue Target***	***Optimal utilization***	r_3
S_4	Very high	Expensive	Surplus	Congestion	r_4

The following section describes the RL evaluation and the integration of both users' and operators' preferences.

4.3.1 Q-Learning Algorithm Evaluation

The focus of this research remains the efficient management of the pool of resources in the HWN to minimize congestion, with the aim of enhancing both users and operators utilities in every state of the network. Y V Kiran *et al* in [44], proposed an approach for network providers to learn the best pricing strategy in the market place using the RL framework. The price entity is modelled as an agent learning the best pricing strategy based on the available fixed set of actions executable in different HWN utilization states.

For evaluation purpose, the percentage of demand for service is demarcated in a proportional manner, as shown in Table 4.2. The *'goal state'* is the desired state (state 3), where both the users' and operators' preferences have been carefully collaborated.

Table 4-2: Possible Scenario of Demand for service in HWN and associated states

Percentage Demand for service	Meaning of scenarios
$S_1 = (0 \le dS_1 \le 25)\,\%\,C_{mk}$	Underutilized state
$S_2 = (26 \le dS_2 \le 50)\%C_{mk}$	Fairly utilized state
$S_3 = (51 \le dS_3 \le 85)\%C_{mk}$	**Goal state**
$S_4 = (86 \le dS_4 \le 100)\%C_{mk}$	Congestion state

From the table 4.3, there exists a relationship between the percentage demand and threshold capacity of the HWN. Let the threshold for the new and handoff calls in the HWN be denoted as T_p and T_q respectively. New calls are only accepted at 86% demand on total capacity ($T_p \le$ 86% of capacity), while handoff calls are dropped only when percentage demand is at 100% of total capacity (T_q = 100% of capacity). Figure 4.4 gives an illustration of the relationship between percentage demand demarcation and capacity threshold in state four.

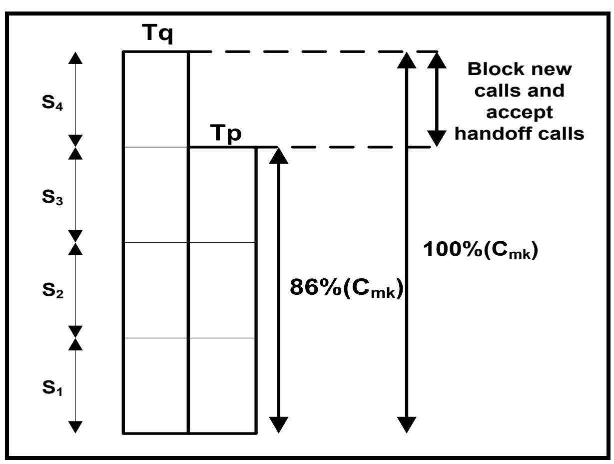

Figure 4-4: Relationship between capacity threshold and percentage demand demarcation

Using a Q-learning technique in this work, a policy for the network price entity is determined for the network to make intelligent decisions that will enhance utilization of radio resources. The reinforcement learning is employed in this research to enable the network learn how to drive the network utilization to the goal state from each state, by choosing a price policy that will enhance users' and operators' utility for each state-action pair.

The transition probabilities of the four states considered can be represented in the Figure 4.5 below. Adopting the first order Markov chain in [45], at a discrete time, the HWN will be at one of the four states $[S_1, S_2, S_3, S_4]$.

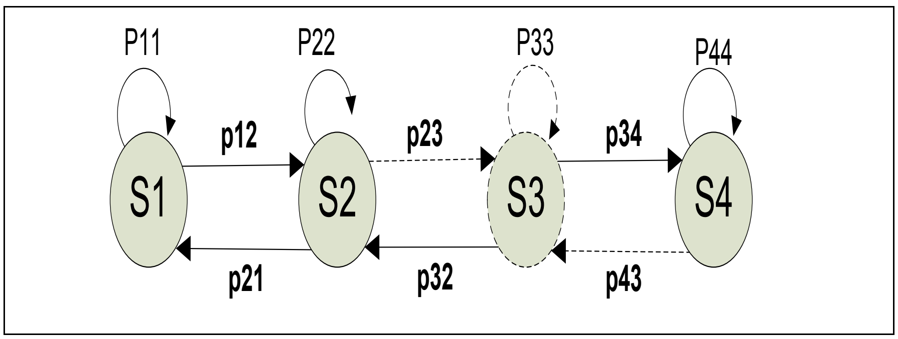

Figure 4-5: State transition diagram of HWN

The state probability vector is the probability of being in one of the four states $(s \in S)$ identified. State probability vector is given as [P_1, P_2, P_3, P_4] and $\sum_{s=1}^{4} P_s = 1$.

The probability transition matrix, P for the ten transition states considered will be given as follows:

$$|P| = \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{21} & P_{22} & P_{23} & 0 \\ 0 & P_{32} & P_{33} & P_{34} \\ 0 & 0 & P_{43} & P_{44} \end{bmatrix}$$

$$\sum_{a=1}^{4} P_{s,a} = 1, \forall s \in S$$

The probability, $P_{s,a}$ that a state transition occur, depends on the state-action pair in a call arrival or departure event. The states have different price depending on the utilization of the network, therefore prices are not fixed to a particular state. In Figure 4.5 above, the price change is observed as the state of the HWN changes. As a result, the network is dynamically priced as the network load changes while considering users' and operators' preference.

It is noteworthy that the traditional approach of modelling the MDP is dynamic programming (DP). Dynamic programming is sufficient enough to give optimal solutions to the MDPs. Therefore, obtaining theoretical models for transition probabilities, transition reward and transition times often present tedious mathematical approach to real life problems. DP only requires the values of these quantities and RL has the potential to solve this MDP problem without having to construct theoretical models [36].

The total reward value obtained from the learning process differs for each state scenario examined in this research. Users rely on their WTP values to enhance their monetary and QoS utilities, and on the other hand, the operator will envisage enhancement of revenue, while ensuring the efficient use of radio resources. Therefore, we recognize that both parties will envisage enhancement of their individual utility.

For the purpose of evaluation, the Q-value can be written as given in equation 4.9 below [34] :

$$Q(s,a) = R(s,a) + \gamma \max a\, Q(S',a) \tag{4.9}$$

Q is the Q-value assigned to each state, (s,a) is the state-action pair, R is the reward obtained for visiting a state and γ is the learning parameter with a boundary between 0 and 1 $(0 \le \gamma \le 1)$, it determines how fast or slow a reward is selected.

The equation (4.9) says; the value of taking action, a in state, s is the reward for the state-action pair, plus the product of the learning parameter and the value of the best possible state-action pair for the next state, S'. States which are not linked directly to goal state is assigned a zero value [46]. Therefore, the matrix |R| is the state-action combination with assigned reward values obtained from state-action pair. Matrix |R| is given as:

$$|R| = \begin{bmatrix} R_1 & R_3 & 0 & 0 \\ R_2 & R_4 & R_6 & 0 \\ 0 & R_5 & R_7 & R_9 \\ 0 & 0 & R_8 & R_{10} \end{bmatrix}$$

Where R_1, R_2, R_3….R_{10} are the reward values obtained as transition occurs in the HWN. When a state is reached, a reward Rn is received, which is then used to update the price. This update continues in an iterative manner, until goal state is reached. The Q-values consequently show the converged optimal policy learnt after several episodes of the state-action pair.

The basic Q-learning algorithm is given below:

Algorithm Q-learning based on HWN transition states

Initialize *Q(s, a)*

Repeat choosing HWN state randomly

- Randomly pick *s*; start state, $s \in S$
- Repeat each step till goal state

*choose *a* based on current *Q(s, a)* using ε-greedy

*Do *a* $(a \in A_\Phi)$, observe *R*, next state (S')

*Update *Q* for all episodes as;

$$Q(s,a) \leftarrow R(s,a) + \gamma \max a\, Q(S',a)$$

$s = S'$

The goal of the algorithm is to goal state is reached most of the time. Meaning the algorithm learns from exploration of the states and makes decisions to efficiently incentivize users to make use of the radio resources, through a periodic price update.

4.4 CHAPTER SUMMARY

This chapter presented the performance evaluation of the proposed scheme along with its requirements and limitations. The procedure for obtaining an equilibrium price that will enhance users and operators' utility was also presented. Q-learning algorithm was modelled to obtain a price policy that efficiently incentivizes or discourage users to make calls, taking into account total reward values at each state. Following the demand function, user behavior analysis and the demand and supply curve, a preference table was developed to show a point of surplus of both users and operator. Identifying this positions promote social fairness for both parties. As a result, we made state 3 the goal state, where both parties are assumed to be treated fairly. By examination, state three (3) carefully combines the preferences of users and providers, and thus yielded a price policy that would generate a higher total reward value over time. Consequently, a goal state that enhanced both users' and operators' utility was identified.

5 SIMULATION RESULTS AND DISCUSSION

This section presents the performance of the proposed dynamic pricing scheme, CDPS. The performance is evaluated through numerical simulation considering different scenarios when CDPS was incorporated and when it was not incorporated.

5.1 Simulation Parameters Considered for the Proposed Scheme Dynamic Pricing Scheme (CDPS), in the HWN

The performance of the proposed dynamic pricing scheme is evaluated through numerical simulation conducted with MATLAB. The HWN scenario considered for this research consists of a two RAT that supports three services. The parameters considered are as follows: Capacity for RAT_1= 20 and RAT_2 = 30. The three classes of service considered are class1, class 2 and class 3, having bbu=1, 2 and 4 respectively. An example of classes of service are file download, voice and video for class 1, 2 and 3 respectively. Service rate in RAT 1 and 2 are u_1=1 and u_2=1 respectively. The threshold for new calls, Tp is approximately 86% of the total capacity in each RAT, and threshold of handoff calls, Tq is 100% of the capacity in each RAT. Network price is periodically updated to incentivize or discourage users from making call request at congestion periods, as a result users with low WTP may choose to make connections at later periods. Prices are set within specified range of maximum and minimum price values. The relevant metrics considered are new call blocking and handoff call dropping probabilities, network utilization, operators' revenue and users' utility are examined.

5.2 Effect of CDPS on traffic intensity

Two scenarios are considered in this dissertation. In the first scenario, the prevailing network price is updated by incorporating CDPS, and in the second scenario, the price is updated without using CDPS. Figure 5.1 shows the traffic intensity for a business day- 24 hours [47, 48]. The peak load periods can be seen at 12H00 and 17H00, and low load periods can be seen at late hours and early hours of the day i.e. 22H00 till 06H00. Call intensity drops between two peak periods as can be seen at 14H00 and later shows an increase.

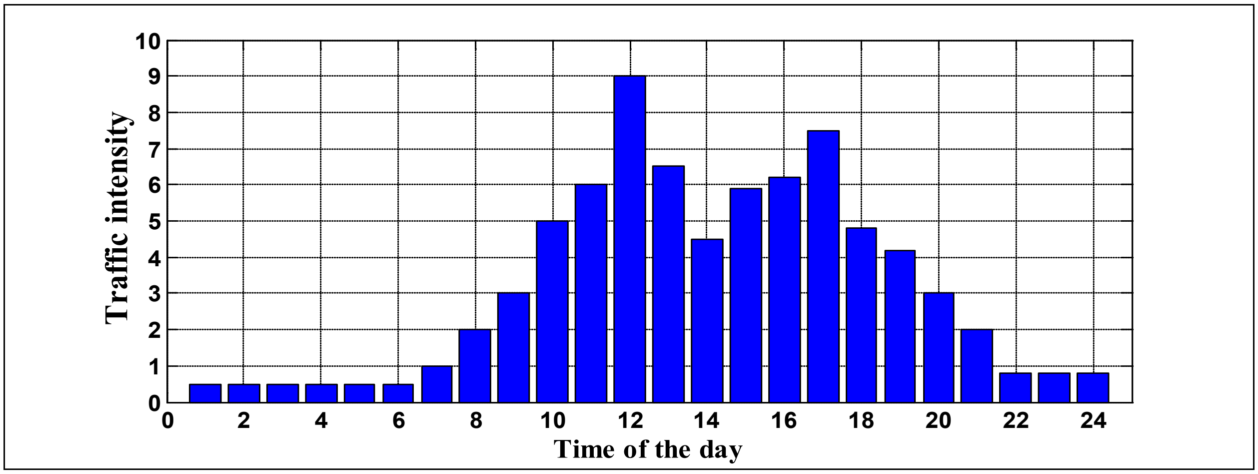

Figure 5-1: Traffic Intensity during a Business Day (24 hours)

By incorporating CDPS as compared to the scheme in [8], an improvement is achieved as shown in Figure 5.2. On the average, the traffic intensity improved, as more users were able to make connections because the equilibrium price obtained by the CDPS incorporates users' willingness to pay and demand shift constant. Recall that demand shift constant, $\sigma_{ij}(t)$ changes with time of the day. Therefore, demand shift constant for low, medium and high period network utilization differed by some constants while evaluating the service price. Consequently, the proposed scheme, CDPS efficiently incentivise users to make calls during low load period and discouraged users during high load periods.

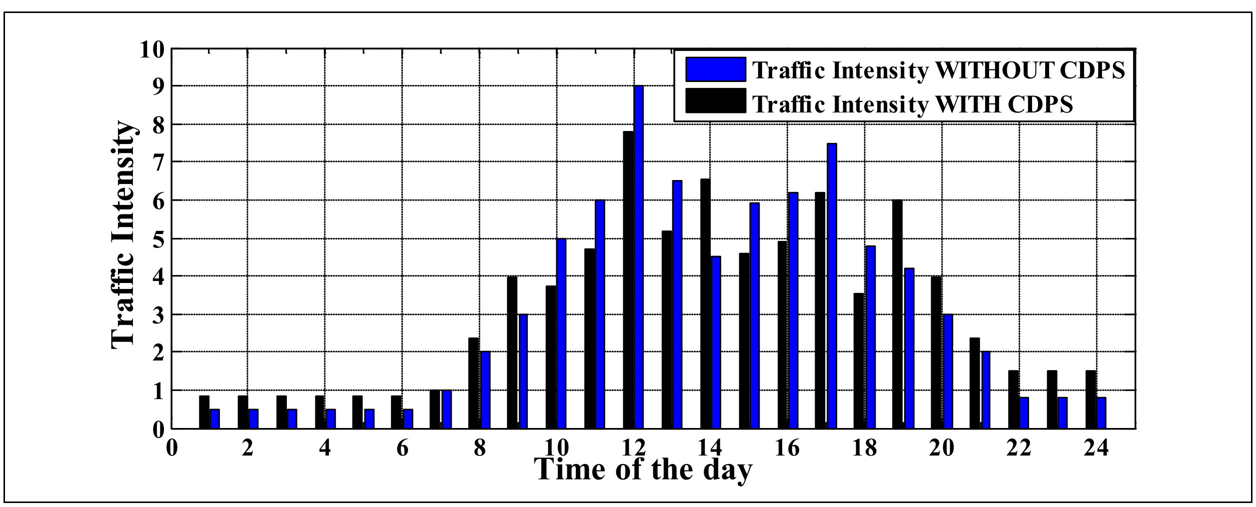

Figure 5-2: Traffic Intensity Improvement with CDPS

Figure 5.2 shows that during high demand period (congestion) i.e. 12H00 and 17H00, the CDPS discouraged users from making calls, while during the low periods i.e. 22H00-06H00, users were incentivised to make call connection. Result therefore shows congestion control and efficient utilization of radio resources.

Figure 5.3 shows price updates on class-1 calls, obtained from CDPS by incorporating users' WTP in service price evaluation. The updated price with CDPS indicates an acceptable but higher price that enhances users' and operators' utility. Higher prices were observed at early and late hours of the day (i.e. 00H00-07H00 and 22H00-24H00), while at peak periods, the updated price was almost the same for the scheme without CDPS for class-1 service.

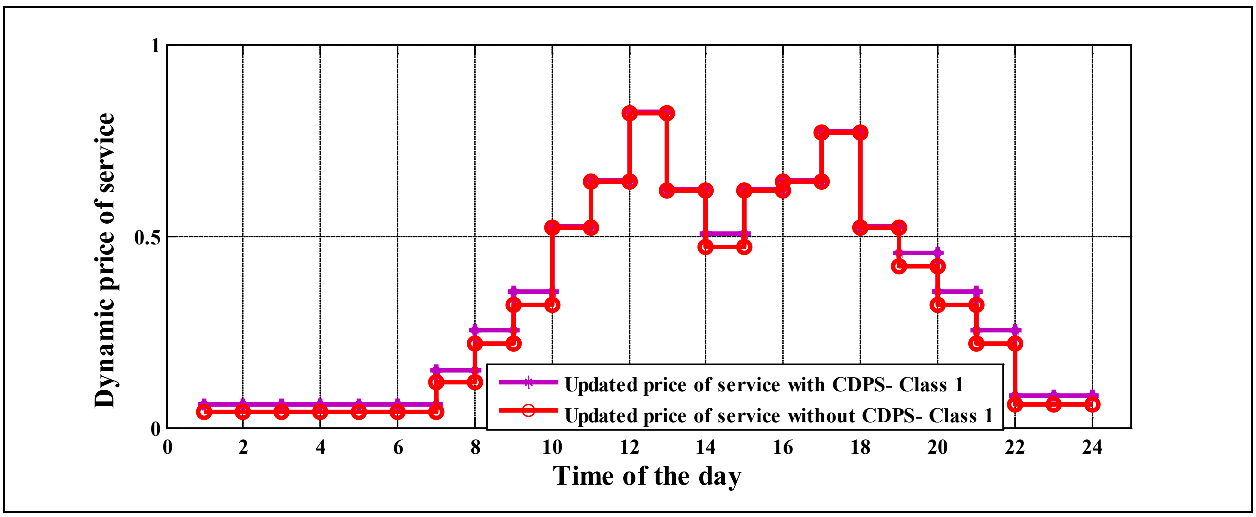

Figure 5-3: Updated service price for class 1 calls

Figure 5.4 shows that some updated price are higher than the historically revealed price. This means that users had a high WTP at some given time. For example updated service price with CDPS shows higher values progressively at 07H00-10H00 and 19H00-22H00, while for other periods, service prices was lower or remained the same as previous values.

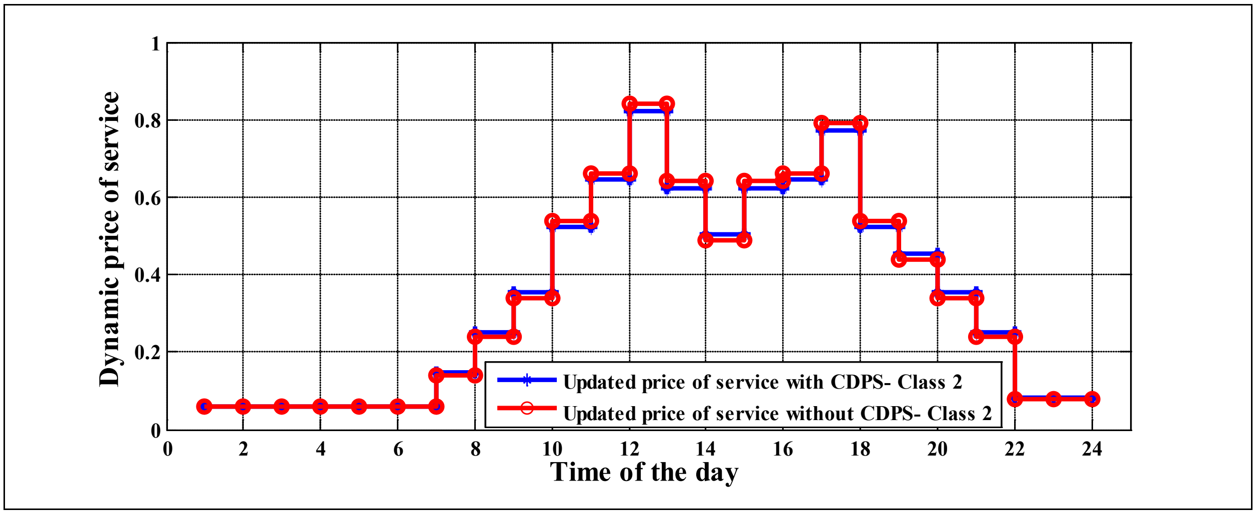

Figure 5-4: Updated service price for class 2 calls

The updated price for class 3 in Figure 5.5 was same during the early hours of the day and adjusted appropriately during other periods. This shows that users had WTP for the updated price. The price of service in a network may be over-priced or under-price, as a result, it is important to ensure an efficient dynamic pricing scheme that captures the demographics of users. CDPS incorporates WTP factor to obtain an equilibrium price that will enhance both users and operators' utilities.

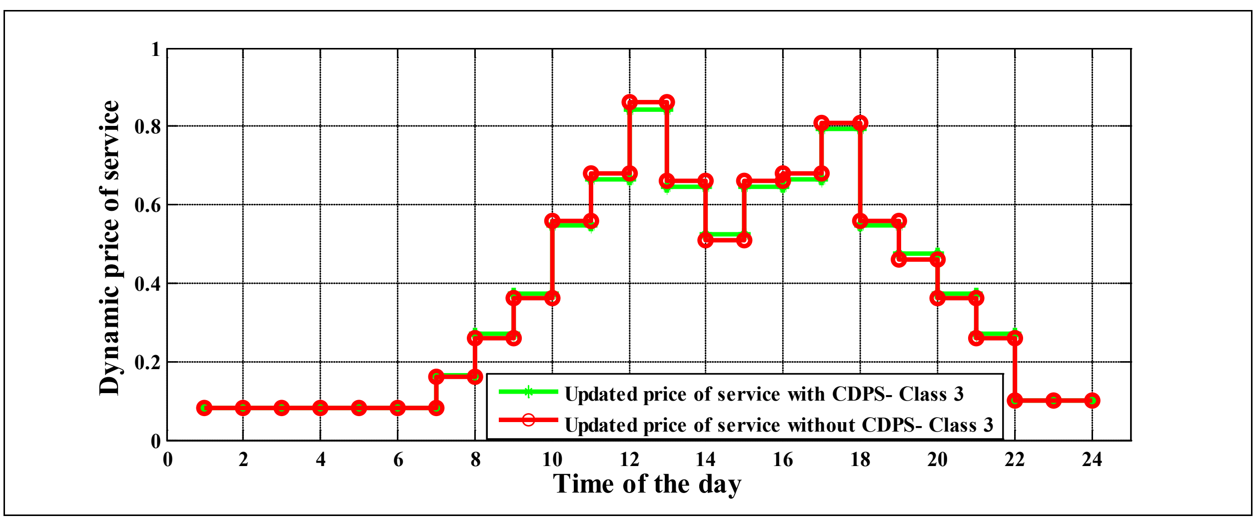

Figure 5-5: Updated service price for class 3 calls

5.3 Simulation Results Showing Q-Learning Convergence to a Price Policy

In this section, the objective is to present simulation results that show the effect of the Q-learning on the proposed dynamic pricing scheme for obtaining an equilibrium price policy. The parameters for the Q-Learning illustration in the HWN considered are as follows: Learning parameter (ɣ) = [0, 0.4, 0.6, 0.8]. HWN utilization states= S_1, S_2, S_3 and S_4, goal state= S_3. State 3 is considered the state with highest total reward in the HWN. Episodes = 1440 (episodes of either arrival or departure of calls).

Recall that Reward ($R_{(s)}$) value is sum of $WTP_{(s)}$ and $REV_{(s)}$, and total reward is the product of the reward and learning parameter (ɣ). Due to the sensitivity of users to price changes, a rating scale is assumed for $WTP_{(s)}$ values so that 90%, 80%, 75% and 50% of users have sufficient willingness to pay when utilization level is at S1, S2, S3 and S4 respectively [12]. In the same vein, utilization of the network has a rating scale of 25%, 50%, 85% and 100% for S1, S2, S3 and S4 respectively, on the condition that users have sufficient willingness to pay for every price update at all utilization levels. The essence of the Q-Learning is to illustrate how the HWN can obtain a price policy that takes into account users and operators' preference in evaluating service price. The reward of each state is tabulated as follows:

Table 5-1: Reward value parameter used for calculating total reward ($TR_{(s)}$)

Utilization state	$WTP_{(s)}$	Network utilization$_{(s)}$	Reward (%)
S1	95%	25%	120
S2	85%	50%	135
S3	65%	85%	150
S4	25%	100%	125

The total reward ($TR_{(s)}$) was computed as given in equation (3.13). The best LP value of

0.8 was chosen. The ε-greedy method was used to choose the state-action pair for succeeding states, based on associated rewards obtained. For further illustration the total reward values and transition states are tabulated below. Table 5.2 shows how $TR_{(s)}$ obtained for the ten transition state scenario considered:

Table 5-2: Total reward obtained and state transition scenarios

State Transition Scenarios/Total Reward (TR)	S_1-S_1	S_1-S_2	S_2-S_1	S_2-S_2	S_2-S_3	S_3-S_2	S_3-S_3	S_3-S_4	S_4-S_3	S_4-S_4
TR(0.8)	75.52	78.40	75.52	78.40	80	78.4	80	77.36	80	77.36

The table shows an improvement in total reward ($TR_{(S)}$) as the utilization changes and as the learning parameter changes.

Deductions made from the total reward shows that the policy converges at the goal state and obtains the highest cumulative total reward, $TR_{(S)}$ values over time, using LP value of 0.8.

The Q-Learning learns by running several iterations as the HWN transits from one state to the other, while selecting the best available actions. Recall that an episode represents a call arrival and/or departure which may be followed by a price update event. Considering a call arrival and/or departure every minute into the HWN over a period of 24 hours gives 1440 episodes in total. Figure 5.6 shows the actual episodes of the Q-Learning algorithm as state transition occurs due to arrival and departure of calls. The changes in states (state 1-4) are as a result of actions taken based on the price and network utilization.

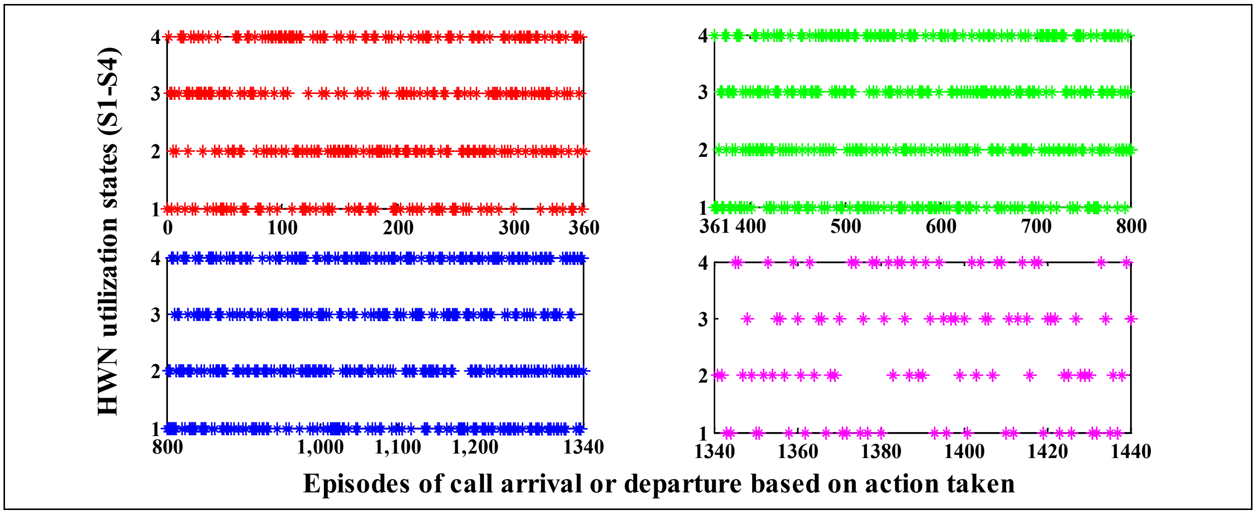

Figure 5-6: Episodes of state-action pair over a 24-hour period

In Figure 5.7, the states within the rectangle (state 2 and 3), shows that the network obtained a better reward value over time. The two extremes of utilization explained earlier which are congestion states (state 4) and underutilized states (state 1) was minimized. Therefore, the optimal price policy obtained was able to keep the HWN running optimally most of the time.

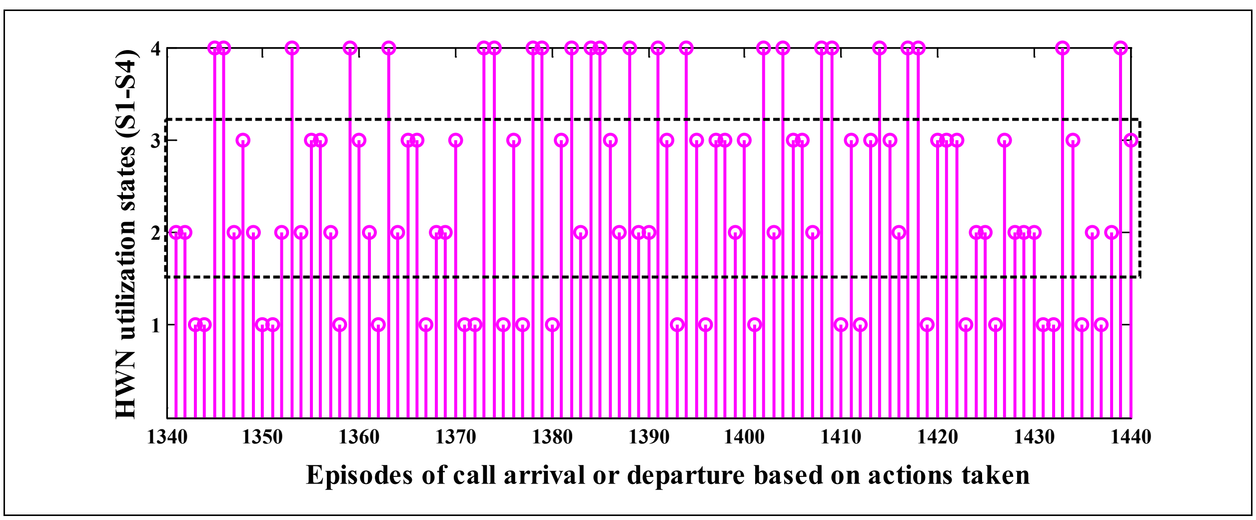

Figure 5-7: Episodes showing changes in HWN state for final 100 episodes

The Q-learning algorithm shows the total reward values obtained over time converged mostly at the goal state and at state two (which can be referred to as the sub-optimal state of the network). Therefore, we can deduced that the network incentivised users to utilize the network efficiently, by ensuring utilization was at goals state and state two most of the time. The Q-Learning shows how the network can incorporate a 'reward-driven' policy to enhance the utilization of the network resources. As a result, both users and operators enhanced their utility.

5.3.1 Effect of CDPS on Users' Connection Request

Using price as the system control vector helps to regulate users demand for connection. However, the objective is to obtain a price that will effectively incentivise users, by controlling congestion and avoiding resource wastage (underutilization). Therefore, an equilibrium price is the price that ensures just enough users are having access to the radio resource in the HWN.

The arrival rate for the three classes of service considered also show an improvement when the CDPS was incorporated for service price evaluation. Figure 5.8, Figure 5.9 and Figure 5.10 shows proposed dynamic pricing scheme improvement on arrival rate, during peak period and low load periods.

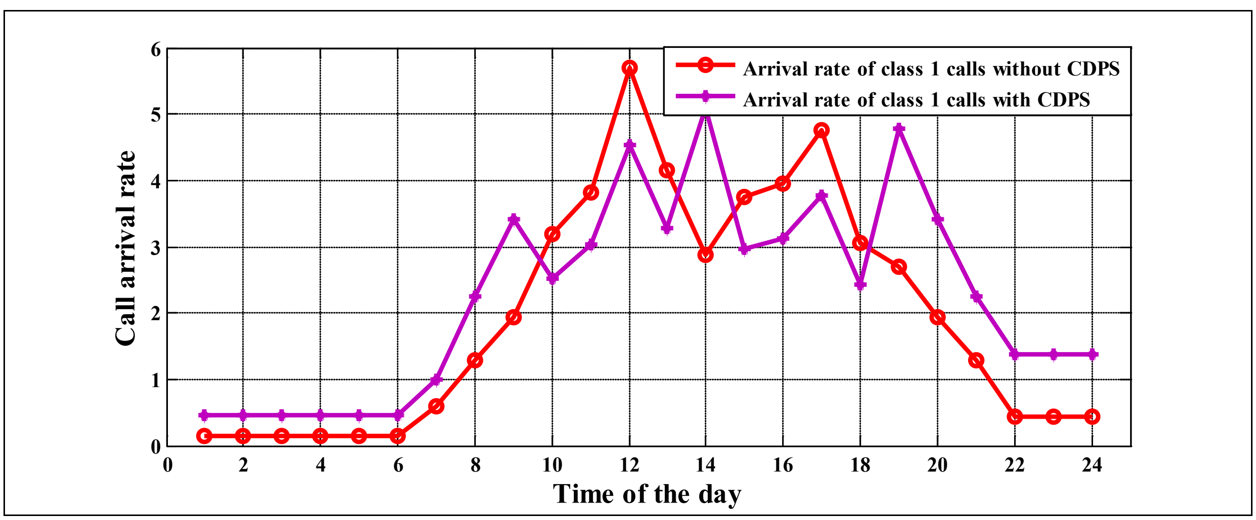

Figure 5-8: Arrival rate of class-1 calls with/without CDPS

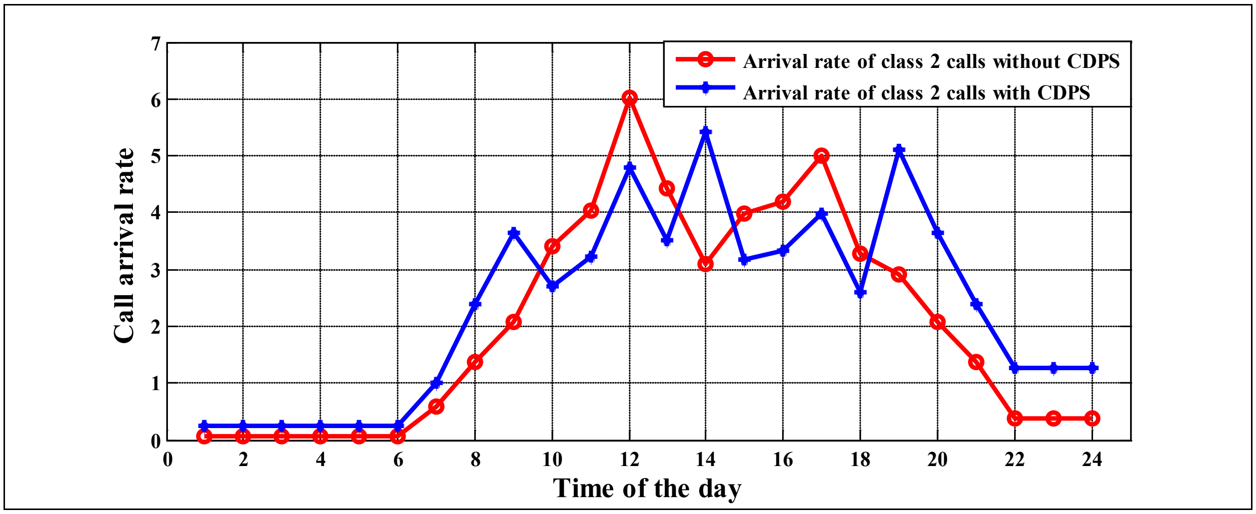

Figure 5-9: Arrival rate of class-2 calls with/without CDPS

The proposed CDPS was able to achieve an improvement on admitting users into the HWN. Over an operational period of 24 hours, the proposed scheme shows improved performance most of the time, especially during peak load periods (11H00-13H00 and 16h00-17h00) and low load periods (mainly 22H00-06H00). This means that the users find the price fair enough and are satisfied to make call requests as the utilization level of the HWN changes. Furthermore, the results show that some users deferred their call request to a later time when an affordable price was updated. Some calls were deferred until 14H00 instead of 12H00, also some users deferred their calls until 19H00 rather than at 17H00.

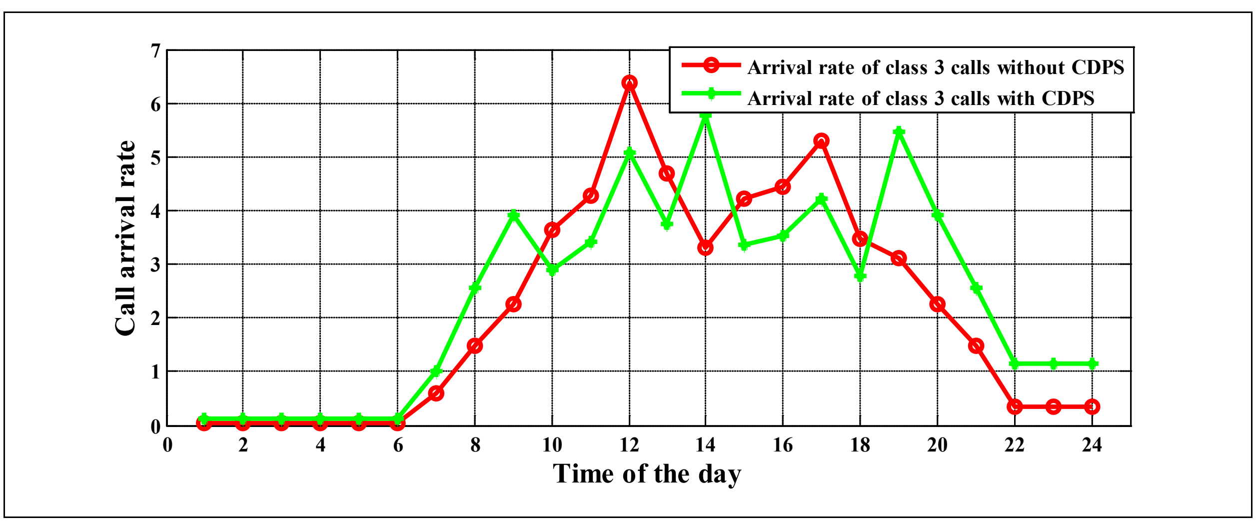

Figure 5-10: Arrival rate of class-3 calls with/without CDPS

The proposed scheme shows an improvement in HWN utilization by updating price access that reduces arrival rate of users during congestion periods while encouraging more arrival at low periods, to reduce wastage of radio resources.

5.4 Congestion Control of the Proposed Collaborative Dynamic Pricing scheme, CDPS

This section presents the congestion control capability of the proposed collaborative dynamic pricing scheme (CDPS). Further investigation on the performance of the proposed collaborative mechanism are validated by the QoS guarantee in terms of the call blocking probability (PB), call dropping probabilities (PD), and overall resource utilization.

Figures 5.11 and 5.12 show the call blocking and call dropping probability of class-1 connections in the HWN with and without using the proposed CDPS.

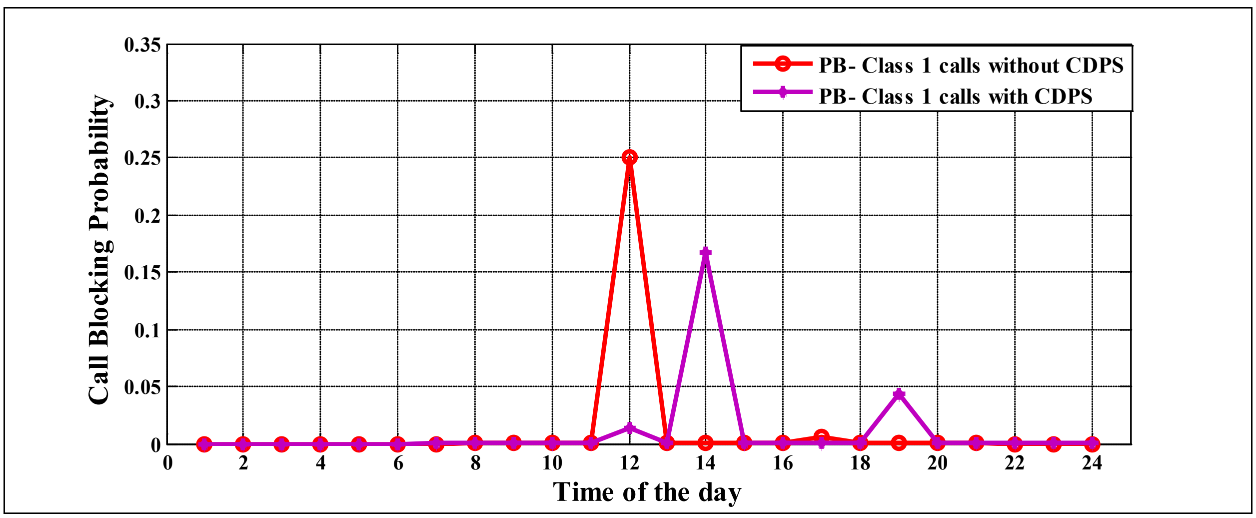

Figure 5-11: Call Blocking Probability on class-1 Calls

Figure 5.11 shows that CDPS kept blocking probability at less than 0.05 for peak period (12H00) and less than 0.2 at 14H00, while the scheme without CDPS showed a high blocking probability of 0.25 during the first peak period (12H00). The CDPS shows that users were incentivised to make connection, as a result there was more intrusion into the network at 14H00 and 17H00, however, call blocking probability was kept at low levels than when CDPS was not incorporated. This means more users were incentivised to utilize the network at 14H00 and 17H00.

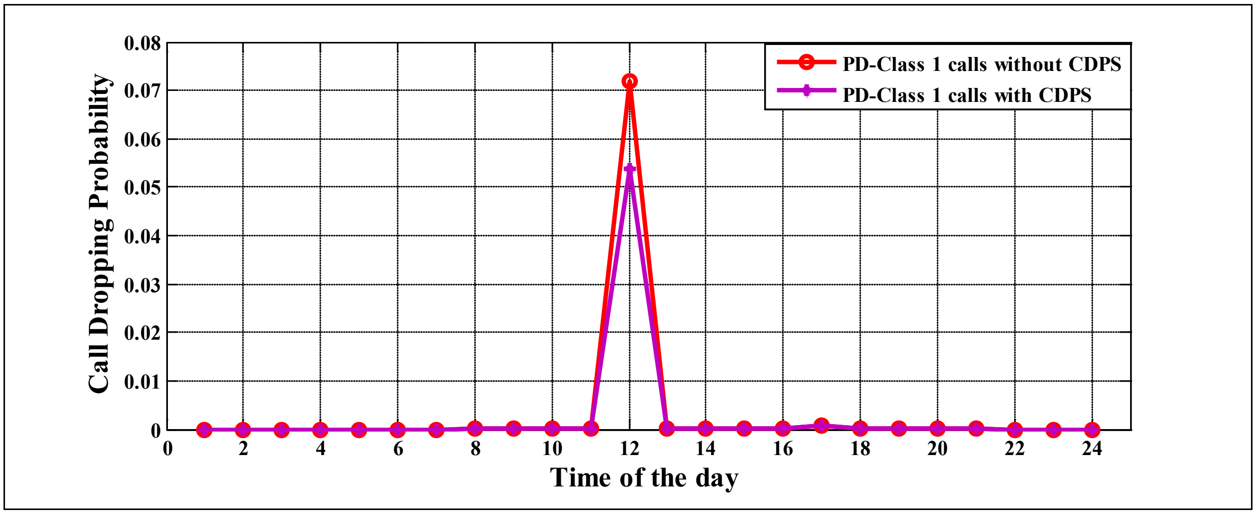

Figure 5-12: Call Dropping Probability on class-1 Calls

In Figure 5.12, the probability of dropping a class-1 call shows high value at peak period (12H00) when CDPS was not incorporated. The overall dropping probability shows an improvement, compared to when CDPS was not incorporated.

Figure 5.13 shows an improvement in call blocking probabilities class-2 calls with the incorporation of CDPS. Results show that call blocking probabilities are reduced considerably as calls arrive into the HWN network. At high arrival rates, CDPS kept blocking probability approximately at 0.25. This goes to show the efficiency of the proposed scheme and that the algorithm is running well at high values of demand.

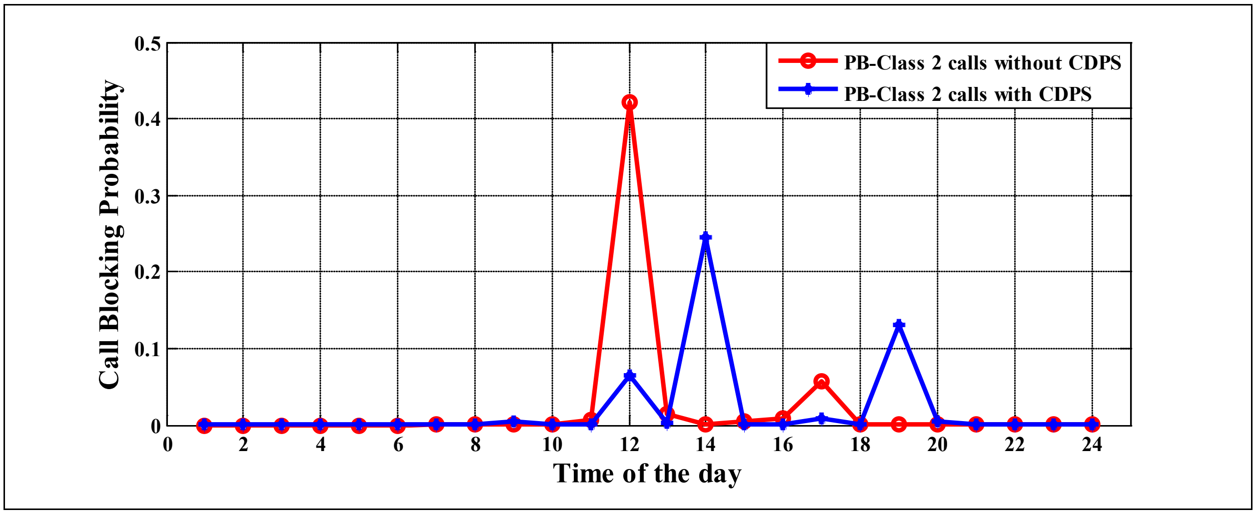

Figure 5-13: Call Blocking Probability on class-2 Calls

Figure 5.13 also shows that users were incentivised to make calls, due to an acceptable price update, as a result call blocking surged at 14H00 and 17H00, nevertheless, the proposed CDPS kept blocking probability at low levels.

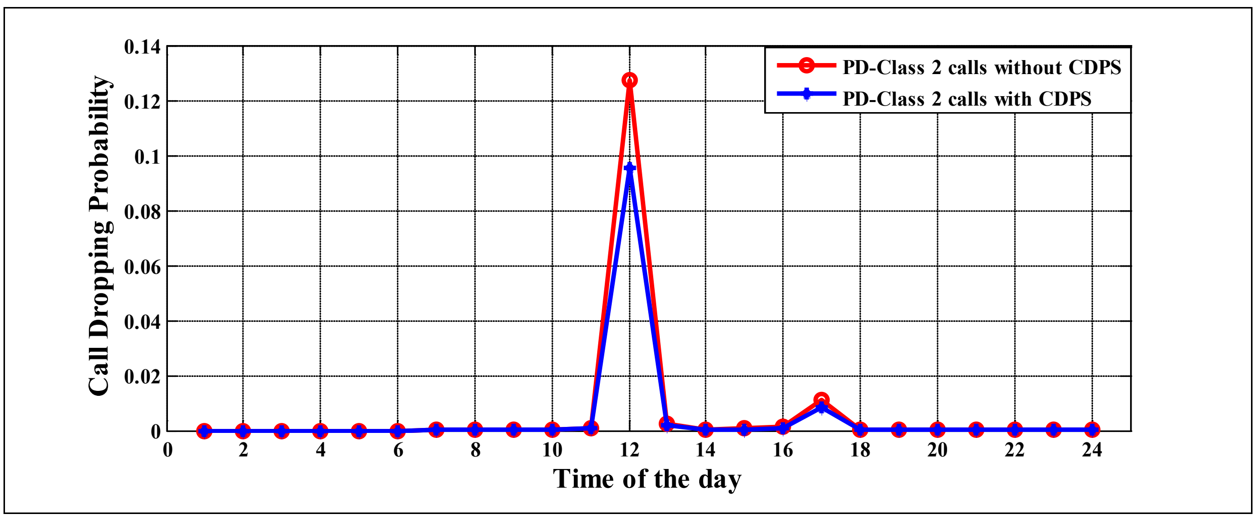

Figure 5-14: Call Dropping Probability on class-2 Calls

Figure 5.14 shows that the dropping probability of class-2 calls was improved with the CDPS scheme. The CDPS obtained a reduction in dropping probability as observed at the peak periods.

Figure 5.15 and 5.16 shows the call blocking and dropping probabilities of class-3 calls respectively. The CDPS shows an overall improvement in the blocking and dropping probability class-3 at the two high peak period (12H00 and 17H00). This shows that CDPS minimized congestion in the HWN.

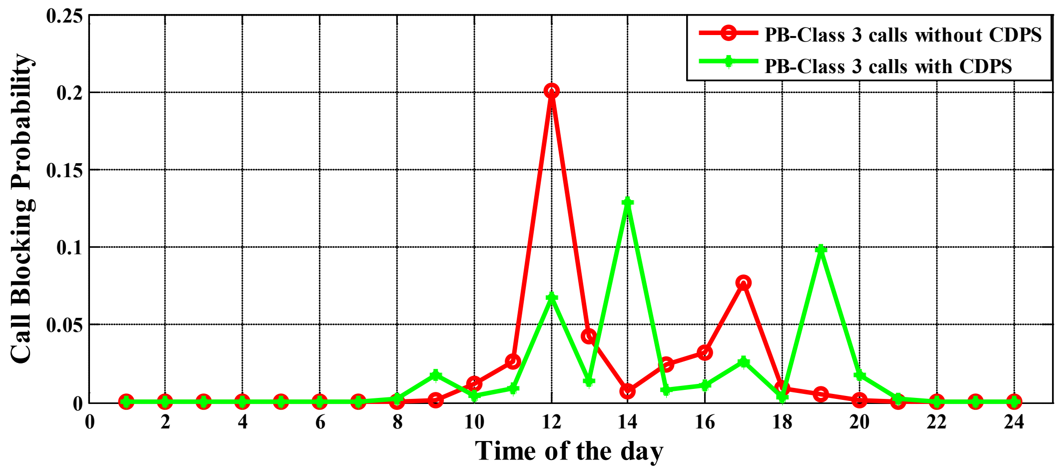

Figure 5-15: Call Blocking Probability on class-3 Calls

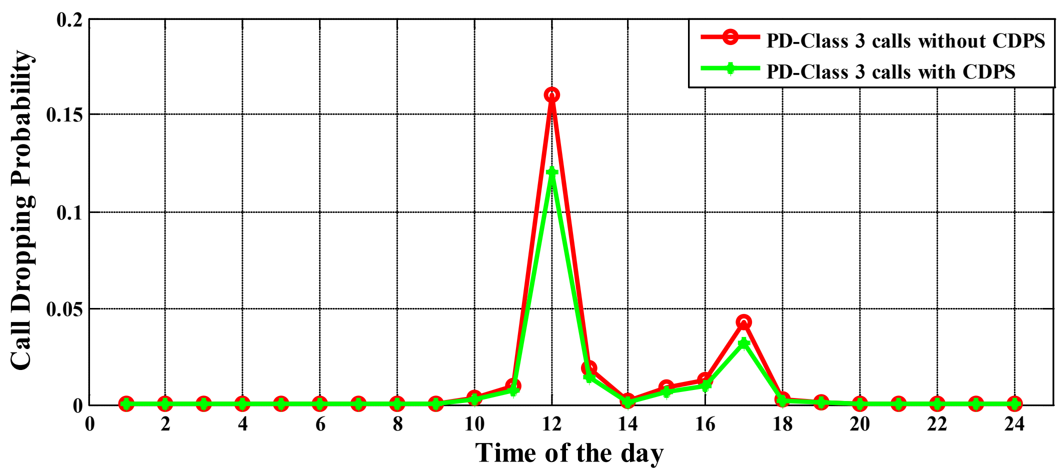

Figure 5-16: Call Dropping Probability on class 3 Calls

From the ongoing discussion of the call blocking and call dropping probabilities of the three classes of service considered, the following were observed:

a. A significant reduction in the blocking probability levels was achieved, illustrating the congestion control feature of the proposed dynamic pricing scheme, CDPS.

b. The QoS utility of the users was enhanced, because the HWN accommodated more users and this showed users satisfaction as new service price was updated and as they utilize the radio resources.

5.5 Users' and Operators' Utility Enhancement using CDPS

This section presents the enhancement of users' and operators' utility. As described earlier, users seek to maximize their QoS and monetary utilities, and operators' seek the maximization of revenue and profit. The operators' revenue is dependent on how efficient the dynamic pricing scheme is able to attract subscribers to utilize the network. Consequently, users' satisfaction enhances the operators' utility. This scheme tagged CDPS was able to integrate users' preferences and operators' preference to achieve an overall enhancement of utility. The following results shows that users' utility and providers' revenue was enhanced effectively during congestion periods and over 24 hours business period.

Figure 5.17 shows the overall QoS utility enhancement of users (U_{Qj}). The network load and price impacts users' satisfaction as they utilize the network resources.

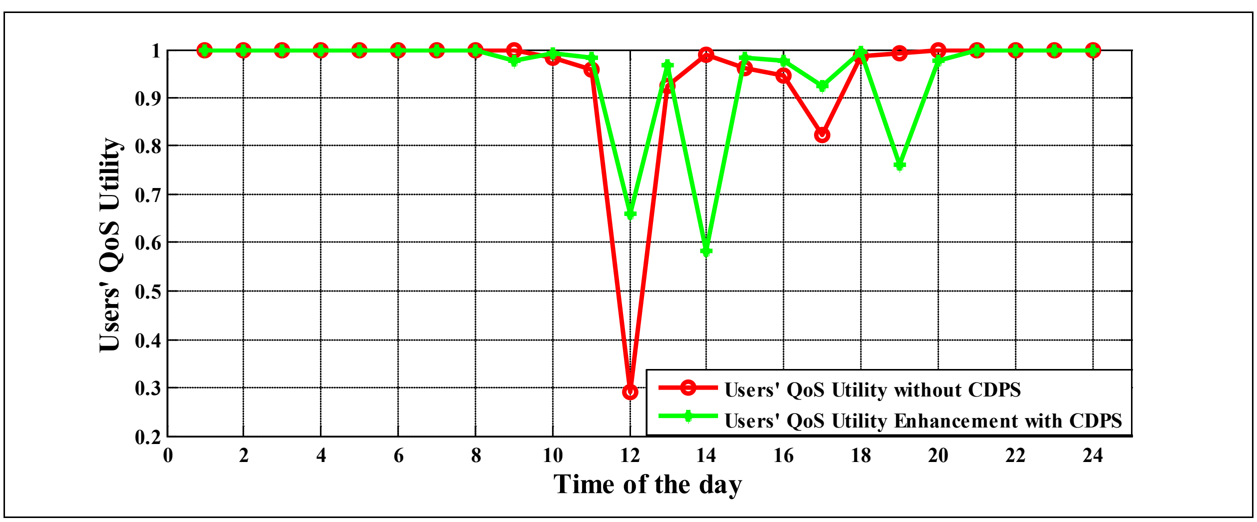

Figure 5-17: Overall users' QoS utility enhancement

It can be observed in Figure 5.17 that users' QoS utility was enhanced at peak periods. At some points, a surge can also be observed due to more network intrusion of users as the updated price incentivise them to make connections, however the QoS utility did not drop low to the level when CDPS was not employed.

Figure 5.18, 5.19 and 5.20 shows users' monetary utility (U_{Mj}) as users make connection request for class-j service and as price changes over a 24-hours business day. As the price of access increases with utilization, a drop in users' monetary utility can be observed, due to users' sensitivity to high service price. However, an improvement was observed with the incorporation of CDPS.

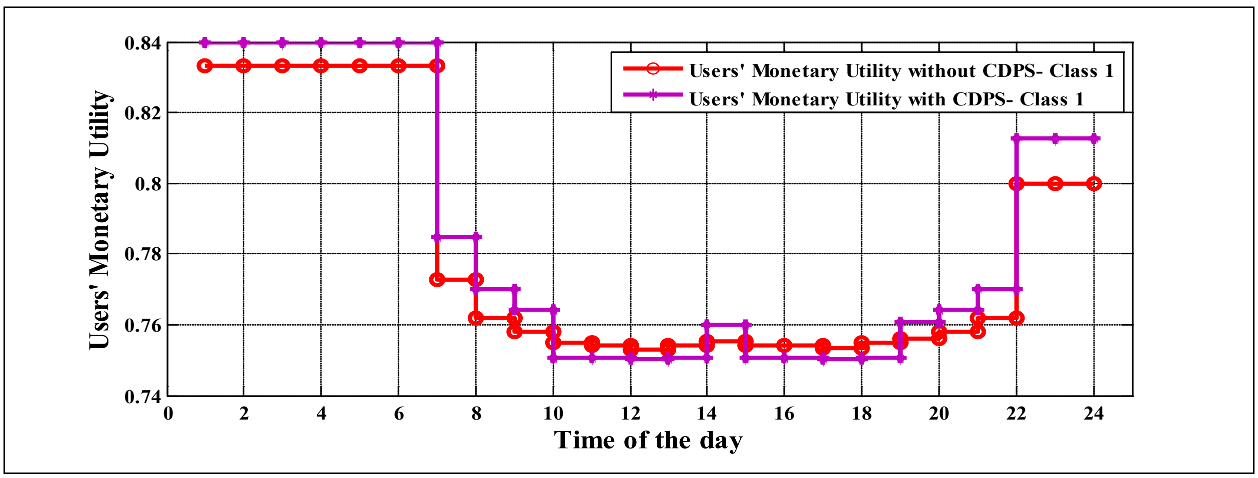

Figure 5-18: Users' Monetary Utility Enhancement on class-1 Calls

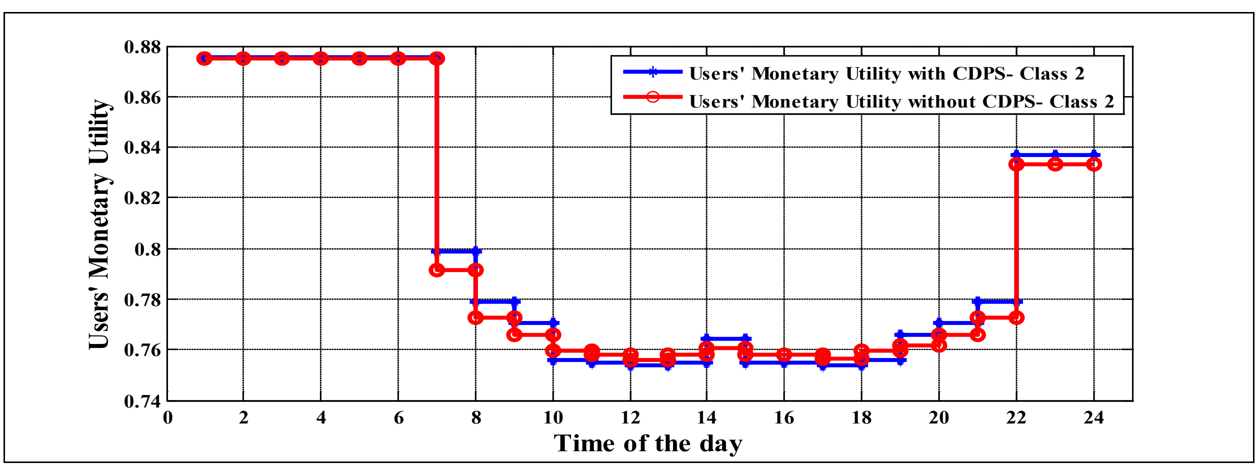

Figure 5-19: Users' Monetary Utility Enhancement on class-2 Calls

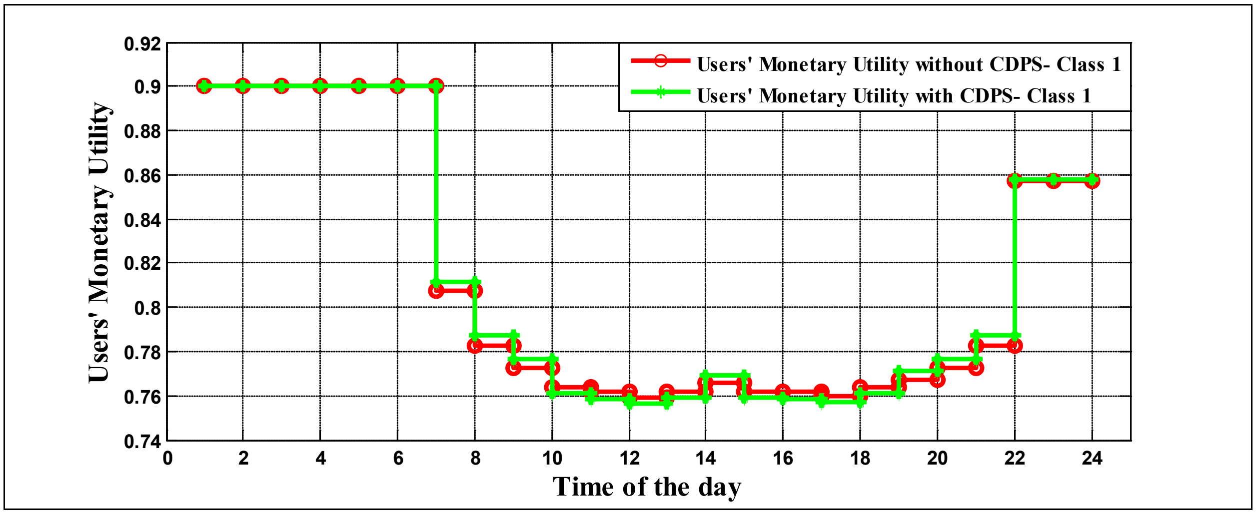

Figure 5-20: Users' Monetary Utility Enhancement on class-3 Calls

Users' monetary utility will differ with respect to demographics and level of income. Therefore, the results may provide different patterns depending on the environment under consideration and demographic distribution of users.

The operators' utility is presented in terms of revenue obtained from the demand for connection over a period of 24 hours. The number of users able to accept the price of access and make connections over every business period determines operators' revenue. From the example given in the table of preference (Table 4.3), the deduction is that operators make more profit at congestion periods, if only more users are able to make call requests not minding the high price.

Figure 5.21, 5.22 and 5.23 shows operators' revenue enhancement on various classes of calls over a 24-hour business period. Higher profits were obtained during congestion periods, based on the users that have willingness to pay for access at that time. CDPS shows a significant revenue enhancement on revenue obtained on classes of calls considered.

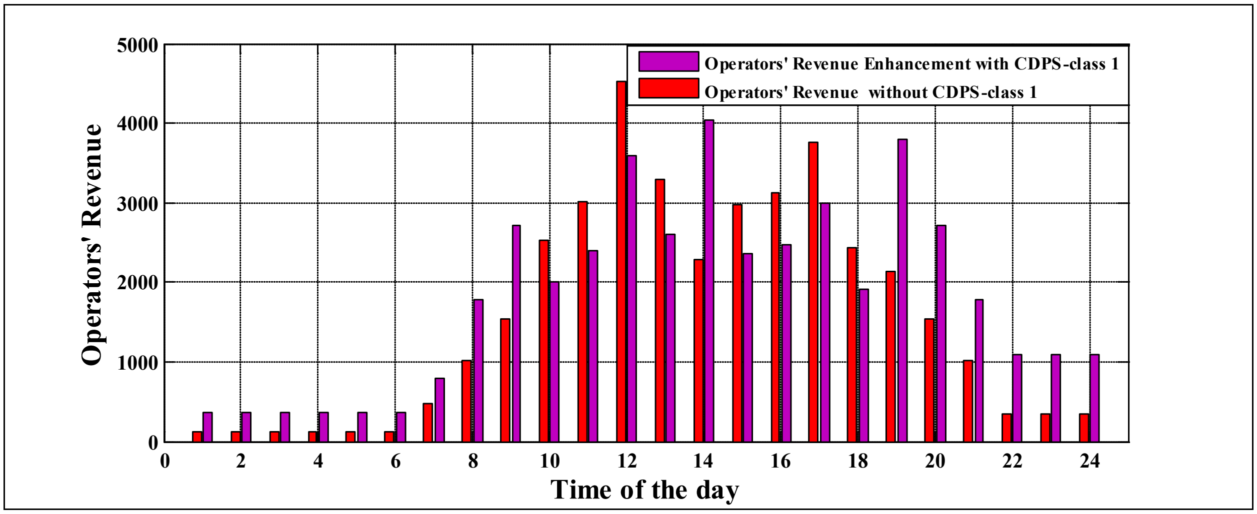

Figure 5-21: Operators' Revenue Enhancement on class 1 Calls

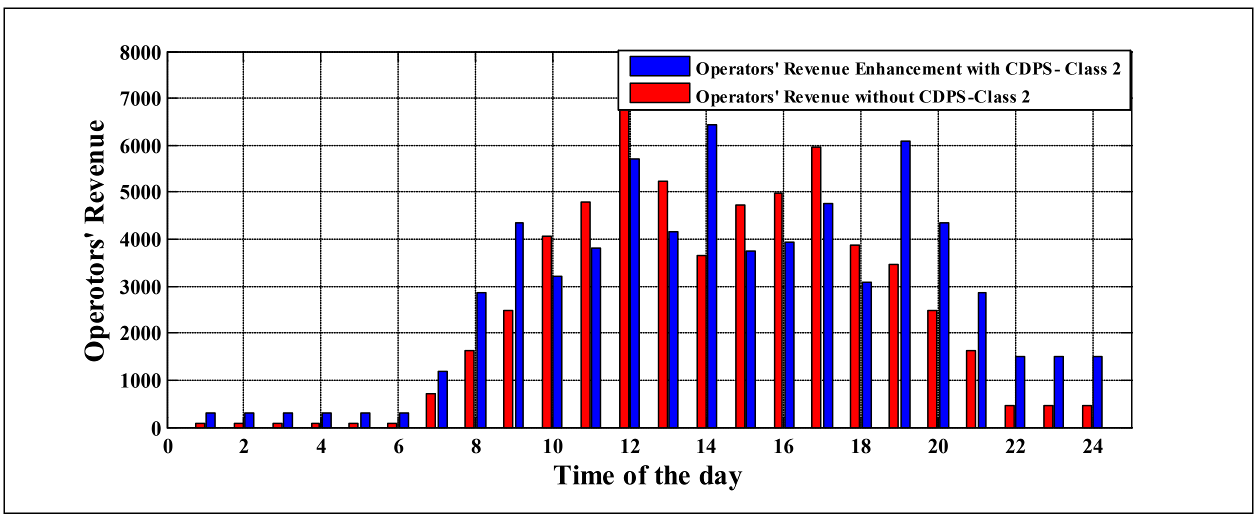

Figure 5-22: Operators' Revenue Enhancement on class 2 Calls

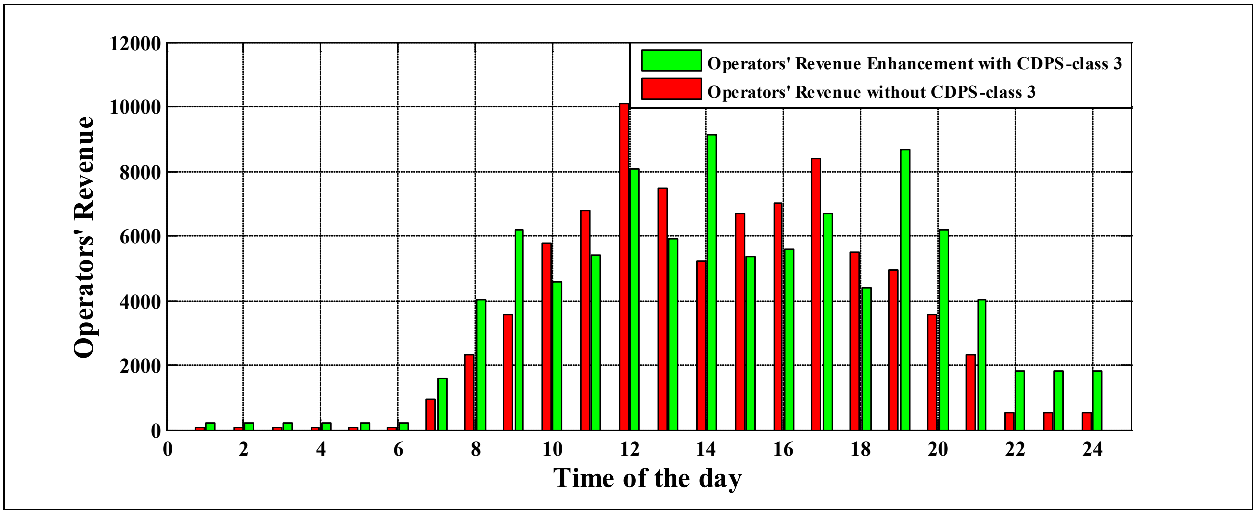

Figure 5-23: Operators' Revenue Enhancement on class 3 Calls

The overall revenue obtained by operator was enhanced when CDPS was incorporated into the HWN. It can be deduced that due to the efficiency of the CDPS the users were satisfied by the access price during low and high period which translated to higher revenue for operators. This was achieved by the incorporation of the users' WTP. The Q-learning algorithm was able to show that higher total reward values are obtained by a 'reward-driven' price policy. As a result, users as well as operators enhanced their utilities.

5.6 CHAPTER SUMMARY

This chapter presented the numerical result and performance of the proposed collaborative mechanism, CDPS. Firstly, the relevant parameter and metrics were outlined. The Q-learning algorithm shows that price update converged to a price policy, by showing an improvement on the total reward obtained. The price policy enables the price entity to efficiently incentivize users to make connections in an event of price changes or update. The effect of equilibrium price update on users' connection request and arrival rate is presented in this chapter. The congestion control feature of the proposed collaborative dynamic pricing scheme was presented by showing reduction in new call blocking and handoff call dropping probabilities for the three classes of service considered. An increased level of utilization showed more network intrusion with efficient management of radio resource usage, meaning more users gained access into the network with significantly low blocking and dropping probabilities. This chapter concluded with results showing users' QoS and monetary utility enhancement and operators' revenue enhancement.

6 CONCLUSION AND RECOMMENDATIONS

This research has revealed that congestion control in multi-serviced HWN using dynamic pricing is an important area of research that determines profitability of operators in heterogeneous wireless networks. Users have been carefully examined as being very important in efficient utilization of radio resources, playing an important role in determining the phase of transformation as the telecommunication evolution changes rapidly. Uncertainties have being observed in terms of the competitive nature of the telecommunications market, and survivability of competitors (service providers). It has been discovered that in existing pricing schemes developed for congestion control in heterogeneous wireless network, much attention has not been given to users' willingness to pay in determining service price. Therefore, a cost-effective scheme known as the Collaborative Dynamic Pricing Scheme (CDPS), has been proposed in this dissertation. The scheme effectively reduces congestion and enhances the utility of users and operators in heterogeneous wireless networks.

The proposed collaborative dynamic pricing scheme employs dynamic pricing for reducing congestion and increasing utilization in the network. Users' sensitivity to price has been observed from their revealed preferences (willingness to pay) or historical market data. This is then used to evaluate equilibrium service price that will minimize congestion and enhance utility.

Furthermore, a Q-learning technique has been developed for the collaborative dynamic pricing scheme. Q-learning algorithm provides an illustration of obtaining a 'reward-driven' price policy that will minimize congestion and underutilization of the HWN. The network therefore develops a price policy that will enable the price entity to choose the best state-action pair for any network utilization level. The performance of the proposed scheme has been evaluated through numerical simulations conducted in MATLAB. Numerical simulation results show that the proposed collaborative approach reduced network congestion and enhances users and operators' utility.

More so, numerical results show that the proposed Collaborative Dynamic Pricing Scheme (CDPS) controls congestion by reducing new call blocking and handoff call dropping probabilities, and enhances the utilities of users and operators. The proposed scheme can enhance the competitive edge of a network operator when implemented in a heterogeneous wireless network.

6.1 Recommendations

This research recommends that the scheme be realized and implemented on a more sophisticated network simulation tool. A prospective radio resource management system, with focus on price dynamics has been proposed to providers, to be realized on a functional telecommunication network. Furthermore, the heterogeneous scenario considered for this research has two RATs. Further work should be looked into to see the effect of increasing number of RATs on the performance of the proposed scheme.

Finally, the users' WTP values should be computed with other user utility and demand functions for better performance and comparison. It is also recommended that users' demographics on network connection requests should be given greater focus to improve on this work.

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