VIRTUALIZATION OF MULTICAST SERVICES IN WIMAX NETWORKS

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ABSTRACT

Multicast service is one of the methods used to efficiently manage bandwidth when sending multimedia content. To improve bandwidth utilisation, virtualization is often invoked because of its additional features such as bandwidth sharing and support of services that require high volumes of transactional data. Currently, network providers are concerned with the bandwidth amount for efficient use of the limited wireless network capabilities and the provision of a better quality of service. The virtualization design of a multicast service framework should satisfy several objectives. For example, it should enable the interchange of service delivery between multiple networks with one shareable network infrastructure. Also, it should ensure efficient use of network resources and guarantee users' demands of Quality of Service (QoS). Thus, the design of virtualization of multicast service framework is a complex research study.

Due to the bandwidth-related arguments, a strong focus has been put on technical issues that facilitate virtualization in wireless networks. A well-designed virtualized network guarantees users with the required quality service. Similarly, virtualization of multicast service is invoked to improve efficient utilisation of bandwidth in wireless networks. As wireless links prove to be unstable, packet loss is unavoidable when multicast service-oriented virtual artefacts are incorporated in wireless networks.

In this thesis, a virtualized multicast framework was modelled by using Generalized Assignment Problem (GAP) methodology. Mixed Integer Linear Programing (MILP) was implemented in MATLAB to solve the GAP model. This was to optimise the allocation of multicast traffic to the appropriate virtual networks. Thus, the developed model allows users to have interchangeable services offered by multiple networks. Furthermore, Network Simulator version 3 (NS-3) was used to evaluate the performance of the virtualized multicast framework. Three applications, namely, voice over IP (VoIP), video streaming, and file download have been used to evaluate the performance of a multicast service virtualization framework in Worldwide Interoperability for Microwave Access (WiMAX) networks using NS-3. The performance evaluation was based on whether MILP is used or not used.

The results of experimentation have revealed that there is good performance of virtual networks when multicast traffic is sent over one single virtual network instead of sending it over multiple virtual networks. Similarly, the results show that the bandwidth is efficiently

used because the multicast traffic is not delivered through multiple virtual networks. Overall, the concepts, the investigations and the model presented in this thesis can enable mobile network providers to achieve efficient use of bandwidth and provide the necessary means to support services for QoS differentiations and guarantees. Also, the multicast service virtualization framework provides an excellent tool that can enable network providers to interchange services. The developed model can serve as a basis for further extension. Specifically, the extension of the model can boost load balancing in the flow allocation problem and activate a virtual network to deliver traffic. This may rely on the QoS policy between network providers. Therefore, the model should consider the number of users in order to guarantee improved QoS.

DEDICATION

In memory of my parents

Eliackim Ushizimpumu and Zilippa Nyirangoboka

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NOMENCLATURE

16QAM	16 Quadrature Amplitude Modulation
64QAM	64 Quadrature Amplitude Modulation
AAA/PF	Authentication, Authorization, Accounting / Path Flow
AP	Access Point
API	Application Program Interface
ASN	Access Service Network
ASN_Devs2	Access service Network Device 2
ASNGW	Access Service Network Gateway
ASP	Access Service Provider
BE	Best Effort
BPSK	Binary Phase Shift Keying
BSs	Baste Stations
CDMA	Code Division Multiple Access
CID	Connection Identifier
CPS	Convergence Part Sublayer
CS	Connectivity Sublayer
CS	Connectivity Sublayer
CS SAP	Connectivity Sublayer Service Access Point
CSN	Connectivity Service Provider
CTC	Convolutional Turbo Code
DL/UL	Downlink/Uplink
DSL	Digital Subscriber Line
DSx	Dynamic Service messages
E1/T1	Digital Interfaces
EFR	Enhanced Full Rate
E-MBS	Enhanced Multicast Broadcast Services
EMBS-MAC	Enhanced Multicast Broadcast Service MAC
ertPS	Extended Real-Time Polling Service
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplex
FEC	Forward Error Correction

FreeBSD	Free Berkeley Software Distribution (Unix like OS)
FTP	File Transfer Protocol
FTP	File Transfer Protocol
FTP	File Transfer Protocol
GAP	Generalized Assignment Problem
GENI	Global Environment for Network Innovations
GNU	GNU's Not Unix
GPLv2	General Public License version 2
GRE	Generic Route Encapsulation
GSM	Global System for Mobile communications
HTTP	Hyper Text Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
InPs	Infrastructure Service Providers
IP	Internet Protocol
IPTV	Internet Protocol Television
IPV4	Internet Protocol Version 4
ISPs	Internet Service Providers
IT	Information Technology
ITU_RBT B06	Radio-communication sector of ITU Broadcasting service (Television)
KP	Knapsack Problems
KVM	Kernel based Virtual Machine
LAN	Local Area Network
LoS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAC SAP	MAC layer Service Access Point
MAN	Metropolitan Area Network
MBS	Multicast Broadcast Services
MCBCS	Multimedia Multicast Broadcast Services
MCGS	Multicast Groups
MCV	Multicast Virtual Server
MG	Multicast Group
MIIS	Media Independent Information Service

MILP	Mixed Integer Linear Programing
MPEG	Moving Picture Experts Group
MPLS	Multi-Protocol Label Service
MS	Mobile Station
NAP	Network Access Providers
NGN	Next Generation Network
NIC	Network Interface Card
NLoS	Non Line of Sight
NOs	Network Operators
NP	Network Provider
nrtPS	Non-Real Time Polling Service
NS-3	Network Simulator Version 3
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Divisions Multiplex Access
OS	Operating System
PFS	Path Flow Service
PHY	Physical Layer
PHY SAP	Physical Layer Service Access Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
QUEMU	Quick Emulator
RAN	Radio Access Network
rtPS	Real-Time Polling Service
SAVI	Smart Application on Virtual Infrastructure
SDN	Software Defined Network
SDU	Service Data Unit
SFA	Service Flow Authorization
SFN	Single Frequency Network
SLA	Service Level Agreement
SPs	Service Providers

SRIOV	Single Root Input/Output Virtualization
SSs	Subscriber Stations
TDD	Time Division Duplexing
TDM	Time division multiplex
TV	Television
UCLPv2	User Controlled Lightpath Version 2
UDP	Unit Data Protocol
UGS	Unsolicited Grant Service
UMTS	Universal Mobile Telecommunications Service
VINI	Virtual Network Infrastructure
VIOLIN	Virtual Internetworking on Overlay Infrastructure
VLAN	Virtual Local Area Network
VM	Virtual Machine
VMCBCS	Virtual Multicast Broadcast Services
VNP	Virtual Network Provider
VNs	Virtual Networks
VoIP	Voice over IP
Vos	Virtual Operators
VPN	Virtual Private Network
VRF	Virtual Routing and Forwarding
WAN	Wide Area Network
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WMAN	Wide Metropolitan Area Network

CHAPTER 1

1 INTRODUCTION

1.1. Research Background

In previous years, the Information Technology (IT) field was separated from the network field. Business people, however, realised that there is no IT without networking [1]. For this reason, they decided to combine IT and networking and build a joint infrastructure. In this case, it was discovered that the wired network provides high throughput because of its stability in bandwidth. The wired network has some drawbacks in that it cannot provide internet access to all areas. Thus, the wireless networks that provide radio access today were introduced to reduce the number of cables in network installation. Accordingly, this allowed access to users in remote areas [2].

Nowadays, various radio access technologies exist worldwide. These are WiMAX, Wireless Fidelity (WiFi), and Long Term Evolution (LTE) to name but a few. Radio access technologies have gained considerable momentum to develop at an ever-growing pace, due to the constant growth of mobile computing platforms [2]. Effectively, the existing bandwidth is being consumed at a tremendous rate. Thus, bandwidth users no longer benefit from the services they are provided with because of poor throughput quality. This is due to some demands in sharing the network infrastructure and other network resources. As a result, users are classified into different categories based on their quality of service demands. These users receive the same quality of service if they experience the same channel conditions and have requested the same multicast content.

Globally, in the past, some researchers [3] tried to solve bandwidth management problems to accommodate users efficiently. Frameworks were designed including the co-operation of more than one wireless access networks. This is done by enabling a user device to receive popular content from different radio access technologies such as Universal Mobile Telecommunications Service (UMTS), LTE, WiFi, WiMAX, and many other similar technologies. However, this has not completely solved the bandwidth management problem.

There remains a waste of bandwidth when the popular content is sent through multiple wireless access technologies instead of using a single wireless access technology. Thus, this thesis has sought to share bandwidth with a single wireless access technology and apply multicasting and virtualization, in order to provide a durable solution to the issue of wireless networks.

It is worth recalling that virtualization started in the field of IT as server virtualization and computer virtualization [1]. Subsequently, this was extended to networking as network virtualization. The main benefit of network virtualization is to enable network dealers to provide differentiated services to their customers by ensuring isolation, programmability and scalability [4], [5]. Recently, Network virtualization was extended in wireless networks for the sharing of resources and building of scale economies. Multiple network dealers collaborated on how to use network resources efficiently without affecting the current ones [1].

Multicast services can be provided over virtualized and non-virtualized WiMAX networks. Surely, multicast services are deployed in WiMAX networks for the efficient use of bandwidth to deliver the same content through the application of a single channel. Thus, virtualization of multicast services can solve the existing bandwidth problems in wireless networks. This is performed via the transfer of the same multicast content that may be streaming media, media download and VoIP over a single virtual network on a single channel. Different WiMAX networks receive content from different networks. In this way, instead of sending the same multicast content through multiple networks, the efficient utilisation of bandwidth allows the subscribers to access different virtual networks to receive multicast content from a single virtual network. Consequently, multicast content activates the customization of services on different networks, where each multicast flow is carried through a virtual network. Accordingly, its available capacity and the load each flow causes to each virtual network materialise. Therefore, WiMAX supports applications, such as video, voice, video conferencing, and VoIP, that require differentiated QoS. However, some of these applications require a minimal transmission rate, or they require low data loss, while other applications require maximum data rate [6].

As stated earlier, virtualization was first used in servers and wired network businesses [1]. However researchers [1], [4], [7]–[15] recently initiated a scientific investigation on the virtualization of wireless networks because of their technological benefits. In a virtualization environment, the network infrastructure is shared by many mobile network operators. Each virtual network can provide customised services to its respective users [1], [16]. Additionally, a virtual network can be isolated to avoid its effects on other virtual networks [17]. Network resources can easily be shared among many virtual networks. Specifically, virtualization of high-speed wireless networks such as WiMAX and LTE [1], [12], [13] has drawn scholars' attention. Although research on the virtualization of high-speed networks tends to be a field in itself, further studies were made on air interface and core network virtualization.

The purpose of this thesis is to discover the value of the virtualization of multicast services in WiMAX networks. Only the formulation of adequate hypotheses and the design of a virtualized multicast WiMAX framework can reveal this. As a matter of fact, the virtualized multicast WiMAX framework enable users to share services located in different networks, thereby solving the bandwidth problem. Sending the same multicast content through a single network to users that belong to the different network can effectively improve the network performance. As a part of transport technology, multicast service has its requirements for wireless networks. However, WiMAX is considered to be a mature technology in which the standards and deployment artefacts are well established [18]. This research has considered that multicast service shall become, de facto, an implementation feature of virtualized WiMAX platforms.

Figure 1.1 shows an end-to-end WiMAX virtualization architecture, with a complete isolation of resources, networks and users, where the physical infrastructure is shared among several virtual networks. Virtual networks are seated on the same physical infrastructure. This is why network providers have to manage virtual networks. The wireless network providers offer multicast services to subscriber stations belonging to different virtual networks. Thus, the content is stored in the servers. For example, the multicast services provided could be video streaming, VoIP, file download, web browsing, and similar communication services. If a user subscribes to a service which is delivered by another network, the user should receive the content through any virtual network. If users subscribe to a network, they usually receive a multicast service sent from that network. However, with the use of virtualization, it is possible to receive multicast services from networks other than the one the users have subscribed to.

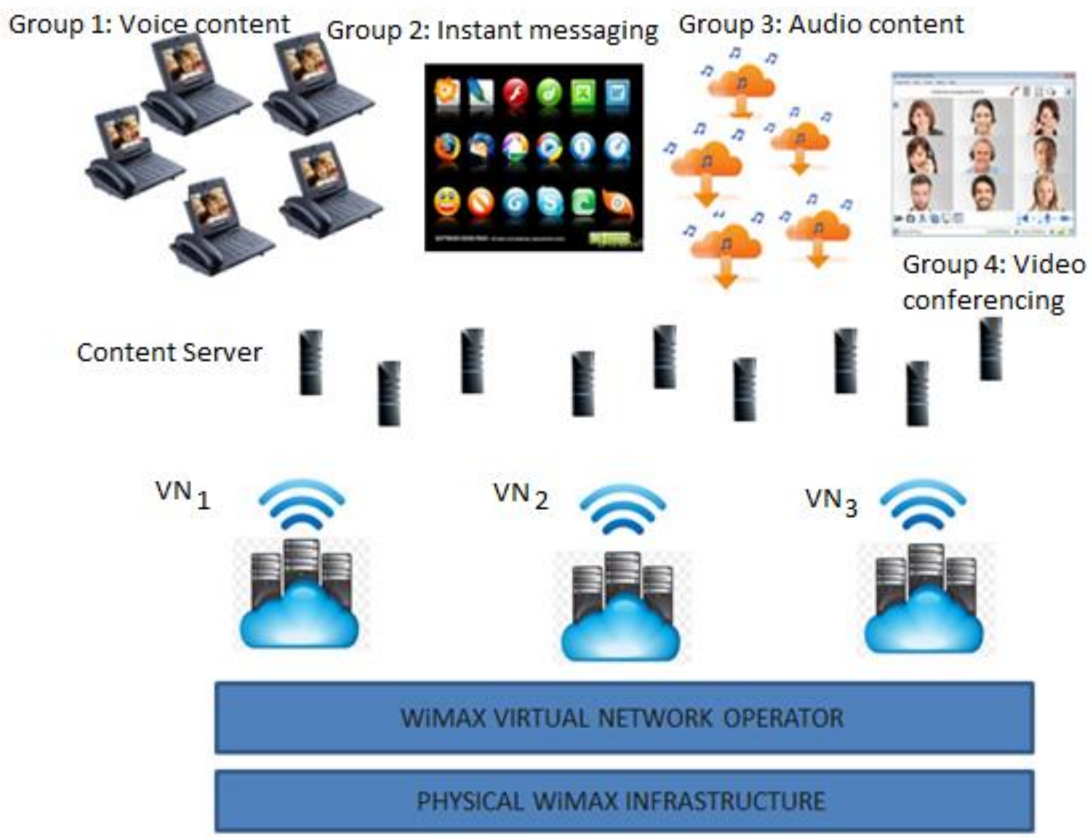


Figure 1.1. Virtualized multicast service in WiMAX network architecture.

1.2. Research Motivation

Business network operators and researchers have experienced bandwidth limitation problems. The need for multicast services to become increasingly large and complex has motivated the writing of this thesis. The initial scheduling solutions for the proposed bandwidth management scheme in wireless networks justified its wide use in multimedia services [3]. However today they experience limitations because of heavy bandwidth traffic demands. The existing framework depends on a limited number of functions within a single network; whereas in today's networks bandwidth processing management has to be performed on multiple networks. For this reason, any capability at a single network is limited to that network.

While the scheduling algorithms depend on the bandwidth management and a single network, a broad approach to multiple networks can trigger the distribution of resource management, as has been already proposed in the mid-1990s [3]. The heterogeneous network approach clarifies the application of multiple networks. Convincingly, the distribution of resource management enables the delivery of the content through any radio access technology, whether LTE, WiMAX or WiFi, and the like. Despite this, the distributed system in heterogeneous networks still suffer from lack of support for the delivery of the same multicast content via a single radio access technology, because the same content is sent through multiple radio access technologies. This is based on networks from which the user will receive the content with the strongest signal. Hence, the network bandwidth is not efficiently used. Similarly, in heterogeneous networks, issues to resolve interoperability and resource allocation among different radio access technologies exist.

There is, therefore, a need for more effective, scalable and flexible ways to access application and data according to subscribers' requirements. Thus, this research aims to design a virtualized multicast service WiMAX in an attempt to enable users to access services from more than one network. Various mobile network operators or providers may decide to offer different services to different users. In this case, virtualization could be a solution. Additionally, virtualization can be used to exploit network services, bandwidth and time resources efficiently. This is where different mobile virtual network operators or providers may use the resources depending on how much they need, or how much they have requested. Although virtualization attempts to solve the above stated problems efficiently, multicasting as a service running over WiMAX network should be considered in a virtualized environment.

1.3. Problem Statement

The inefficient use of bandwidth challenges the proposed selection of access networks and the delivery of multicast content in heterogeneous networks. This is the current situation. Heterogeneous networks are likely to offer multicast services on a relatively large scale. For this reason, the demand for bandwidth to support multicast services is high. If the scarcity of bandwidth in wireless networks is considered, one possible way to address such a bandwidth demand is to apply multicast service virtualization that is efficient in bandwidth management. Whereas efficient management of bandwidth in the current network virtualization may be acceptable in some applications, this research has focused on the most significant heterogeneous networks. This is due to a great demand for bandwidth in such environments. Hence, the network may improve. Specifically, this improvement may come from efficient bandwidth management in the current heterogeneous networks.

Thus bandwidth limitations, with the flow allocation issue, frame the data plane of multicast traffic in the virtualized multicast service framework. One of the main research challenges for the multicast-based system in heterogeneous networks is to find an efficient solution for the bandwidth allocation of multicast traffic. The objective is to allocate flows to networks by using virtualization. This enables multiple virtual networks to run on a single physical network and select the most appropriate virtual networks through which to deliver the traffic. The purpose is to deliver the multicast content, regardless of the network operator the user is subscribed to.

In the literature of heterogeneous networks [3], [19], [20] the multicast content is delivered through multiple access networks that lead to inefficient use of bandwidth. This is a gap that should be filled. Instead of delivering the content through multiple networks, a single network is chosen thereby improving the bandwidth utilization and network performance efficiency. This can be achieved with the application of virtualization that enables multiple virtual networks to coexist in the same infrastructure. Similarly, it facilitates the delivery of multicast content through a single virtual network.

Systematic approaches to select a virtual network and the allocation of traffic to the network have been developed in references [21], [22], [23], [24] and [25] because the inappropriate selection of virtual networks leads to inefficient use of bandwidth. To avoid the user's dissatisfaction, multicast group and optimum rate are to be applied. This is because within virtual networks, at the base station, the scheduling of multicast group was extensively researched in the literature [26], [27], [28], [29], [30], [31], [32] and [33]. Most research efforts in the literature have focused on multicast service delivery through multiple networks.

However to date, no research has been conducted in the delivery of multicast through multiple networks. Similarly, no established technical studies were performed and published in this area. Therefore, virtualization of a multicast service framework is required to solve the bandwidth management gap in wireless systems. Tentatively, the delivery of multicast content through multiple access networks is commonly applied as a solution for multicast shortcomings in heterogeneous networks. Thus, it is against this background that this thesis has sought to respond to the issue of virtualization of multicast services in WiMAX networks.

1.4. Research Objectives

The overall objectives of this research are as follows:

1. To design a virtualized multicast service framework that enables efficient utilisation of network resources.
2. To enable a virtualized multicast service framework to interchange service delivery between multiple networks on a shareable network infrastructure.
3. To develop an algorithm that efficiently allocates multicast traffic in the virtualized multicast service framework, and network performance optimisation.
4. To design an algorithm that selects the optimum multicast rate and scheduling of multicast traffic in the virtual network.

1.5. Research Questions

The design of a virtualized multicast WiMAX network will only be accomplished by answering the following key research questions:

1. How can the virtualized multicast service framework achieve efficient bandwidth management?
2. How can the virtualized multicast service framework enable the interchange of service delivery on a shareable network infrastructure?
3. How can multicast traffic be efficiently allocated in a virtualized multicast service framework and optimise the network performance?

1.6. Research Hypotheses

1. The hypotheses of this research read as follows: A virtualized multicast service framework can efficiently use network resources by providing better network throughput, with reduced delay and jitter.
2. Network resources can be optimally allocated in a virtualized multicast service framework to provide optimum network throughput.
3. Multicast flow scaling can select the optimum dynamic transmission rate for a multicast group and schedule multicast traffic in a virtualized network, with the aim of obtaining the optimum network throughput.

1.7. Contributions

The contributions of this research are the following:

1. The design of a virtualized multicast service framework.
2. The development of an algorithm for bandwidth management that allocates the multicast traffic efficiently to the virtual networks.
3. QoS customization of multicast traffic.
4. Development of a new multicast rate selection algorithm.
5. Development of a new multicast scheduling algorithm.
6. Development of an equation for the estimation of multicast flow throughput.
7. Emulation of multicast services virtualization over WiMAX networks in NS-3.

1.8. Thesis Road-Map

In addition to Chapter 1, which gives the introduction and background to the research, the rest of the thesis is organised as follows:

- Chapter 2 analyses the background theory on WiMAX technology and the concepts of multicasting. It also discusses multicasting in WiMAX and the research related to the objectives of this thesis which are multicast scheduling and network selection in heterogeneous networks in multicasting-based system.

- Chapter 3 covers the background of virtualization in all aspects, namely, server virtualization, network virtualization and wireless virtualization. Similarly, the chapter analyses the literature related to the objective of the thesis on how virtual networks share bandwidth resources.

- Chapter 4 covers the proposed mechanism for virtualization of multicast services in WiMAX networks with the design specification of virtualization for multicast services. This chapter includes the experimental set up of GAP model and the results obtained from the MILP.

- Chapter 5 explains the software representation of the WiMAX module in NS-3, and it describes the implementation of the proposed model in NS-3. It also presents the performance evaluation, which includes the research results and analysis.

- Chapter 6 concludes with how well the research objectives have been achieved, based on how they were defined in Chapter 1. Finally, the chapter discusses some recommendations for future study in the field of virtualization of multicasting services, and provides an overall conclusion that is based on the research objectives and research questions.

CHAPTER 2

2 MULTICASTING IN WIMAX NETWORKS

2.1. Introduction

The chapter discusses the background of WiMAX technology, including different versions of WiMAX: namely fixed WiMAX and mobile WiMAX, and its relevance and benefit. The chapter equally highlights the importance of multicasting techniques and their applications in WiMAX networks. Additionally, multicast broadcast plays an important role in the background of this thesis. Related works, in the context of the multicast broadcast, are explained and discussed from two angles: firstly, they relate to the objective of the thesis which is multicast scheduling in a single network; and secondly, they relate to network selection in multiple networks that are analogous to heterogeneous networks.

2.2. WiMAX Networks

2.2.1. WiMAX Technology

WiMAX is a wireless communication technology which is widely deployed in many developing countries. It was created by WiMAX Forum based on IEEE 802.16 standard. WiMAX was developed to offer high-speed connectivity up to 100 Mbps for mobile users and 1Gbps for fixed users. Thus, WiMAX supports user mobility of up to 120 km/h and users in trains moving at high speeds of more than 350 km/h [34]. Thus, WiMAX provides a high-speed data rate to nomadic or mobile users.

WiMAX network is composed of two main parts: the Access Service Network (ASN) and the Connectivity Service Network (CSN) as described in Figure 2.1. More than one ASN may be present in WiMAX networks to enable the WiMAX network to cover a large area and accommodate a big number of users. This is done when there are many users in an area where one ASN is not enough to service all the users. These are interconnected through the R4 interface. Moreover, more than one CSN can be used as an access network service provider when a large area needs to be covered. This shows part of the subscriber station (SS) connected to ASN through the R1 interface and to CSNs using the R2 interface. CSNs are interconnected through the R5 interface and connected to ASN through the R3 interface. As it is shown in Figure 2.1, NAP is a business entity which is in charge of operating ASN and NSP in charge of operating CSN. In some cases, these two may be the same entity as in this thesis, and it gives the flexibility of accommodating Mobile Virtual Network Operators (MVNOs) which functions as a CSN. Similarly, it allows sharing of the core network server and seamless interworking. This flexibility introduces some challenges in the network discovery and selection procedure in heterogeneous networks. As the WiMAX device should be able to discover NSP behind NAP, it determines which one to connect to and notifies the NAP about its decision. The ASNs is the radio access network which suffers from limited bandwidth resources.

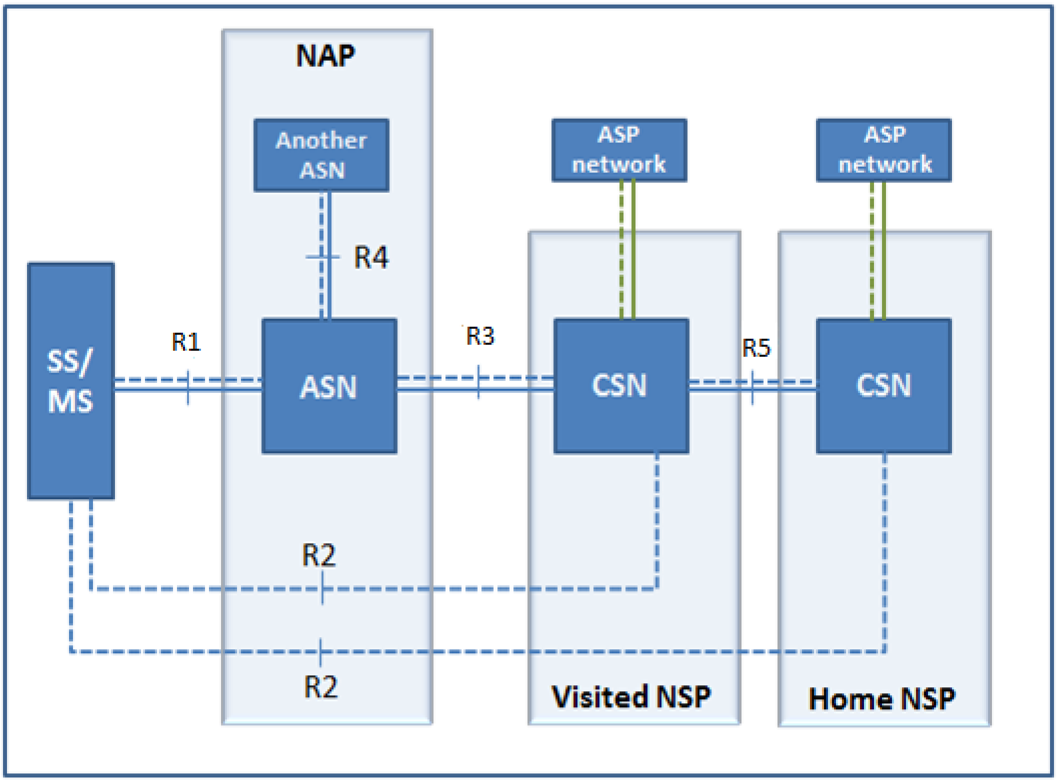


Figure 2.1. WiMAX network reference model [34].

IEEE 802.16 is a standard which defines and develops physical (PHY) and Medium Access Control (MAC) layers of WiMAX. There are two types of IEEE 802.16 standards, namely, fixed wireless access as Wireless Metropolitan Area Network (WMAN) IEEE 802.16-2004, and wireless mobile as Wide Area Network (WAN) IEEE 802.16e-2005 [18]. The fixed network is needed when all the subscriber stations and mobile stations are fixed. However, the mobile network is needed when the subscriber stations are mobile, and the base stations are fixed. The fixed mobile network enables users to receive information data with high throughput compared to the mobile networks. This is due to the many factors that affect and degrade the transmitted signal due to mobile characteristics. In December 2001, the IEEE 802.16 Working Group published the first standards. That was a fixed WiMAX operating in the frequency range of 10-66 GHz for Line-of-Sight (LoS). The working group improved on the existing standards and produced another standard named 802.16a that operated in 2-11 GHz bands in Non-Line-of-Sight (NLoS) [35]. The latter was the improved version because it could operate in the frequency range of 2-11 GHz.

Consequently, it was discovered that the higher the frequency, the better the data rates achieved. Then IEEE 802.16-2004 was developed and replaced the standards developed earlier [35]. Later on, some features of IEEE 802.16-2004 were edited through the enhancement of the MAC layer and the PHY layer for performance improvement. These standards did not have the wireless features which are the main importance of wireless networks. In this thesis, only mobile users were considered; that is why the above standards were not appropriate to this research.

In December 2005, IEEE 802.16e was released according to reference [35]. The mobility, multicast and broadcast features were added to IEEE 802.16-2004 standard which was named mobile WiMAX by WIMAX forum. To enable OFDMA scalability 128, 512 and 1024 FFT sizes were added to the 2048 size. This scalability facilitates the adaptive change in data rates. Thus, IEEE 802.16-2004 supports Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). This may be used in Point-to-Point (PTP) or Point-to-Multipoint (PTM). In FDD mode two different frequencies are allocated to downlink and uplink channels to transmit and receive.

It can happen that while in the TDD mode, the same frequency is shared in the downlink and uplink but in different time slots. Since this research focuses on multicast services, whether FDD or TDD, any of the two methods may be used without affecting the performance of the network. As this thesis deals with the virtualization of multicast services, the QoS classes are needed in the performance evaluation. Therefore, WiMAX MAC layer ensures better performance as QoS requirements and it supports the five QoS classes and, according to their needs, they are scheduled following the descending order of priority as shown in the list below [35]. Each of these QoS classes corresponds to an application, and each application has its QoS parameter constraints and, according to this, these QoS classes facilitate the bandwidth allocation based on their priority and requirements. Brief introduction of service classes are given below, and Table 2.1 shows a comparison between QoS classes:

- Unsolicited Grant Service (UGS)
- Extended Real-Time Polling Service (ertPS)
- Real-Time Polling Service (rtPS)
- Non-Real-Time Polling Service (nrtPS)
- Best-Effort (BE)

Unsolicited Grant Service (UGS) is a class which is used for VoIP application. This requires a maximum sustainable rate and tolerates maximum latency and jitter. As a result, it is characterized by fixed packets data on a periodic basis. Digital Interfaces (T1/E1) and VoIP which has silence suppression features illustrates this.

Extended Real-Time Polling Service (ertPS) is used for voice activity detection (VoIP) application. This requires a minimum reserved rate with a maximum latency tolerance, minimum sustainable rate, and it tolerates jitter because it has characteristics of variable size data packets on a periodic basis. Moving Picture Experts Group (MPEG) videos and E1/T1 illustrates this.

Real-time Polling Service (rtPS) is used for streaming video or audio and requires minimum reserved rate, a maximum sustainable rate , and tolerates latency at a maximum value with high traffic priority.

Non-Real-Time Polling Service (nrtPS) is used for File Transfer Protocol (FTP) applications and requires minimum reserved rate, maximum sustainable traffic rate, with high traffic priority (variable sized data).

Best Effort (BE) is used for transferring the data web browsing applications and requires a maximum sustainable rate and high traffic priority. In defining the QoS classes, the maximum and minimum values mentioned for each QoS class are given in Section 4.7.

Table 2.1 Comparison of WiMAX QoS Classes [35]

QoS	**Advantages**	**Disadvantages**
UGS	No overhead; meets guaranteed latency for real-time service.	Bandwidth may not be utilised fully since allocations are granted regardless of current need
ertPS	Optimal latency and overhead efficiency	Needs to use the polling mechanism (to meet the delay guarantee) and a mechanism to let the BS know when traffic starts during the silent period
rtPS	Optimal data transport efficiency	Requires the bandwidth overhead request and the polling latency (to meet the delay guarantee)
nrtPS	Provides efficient service for non-real time traffic with minimum reserved rate	Not Applicable
BE	Provides efficient service for BE traffic	No service guarantee; some connection may starve for long periods of time.

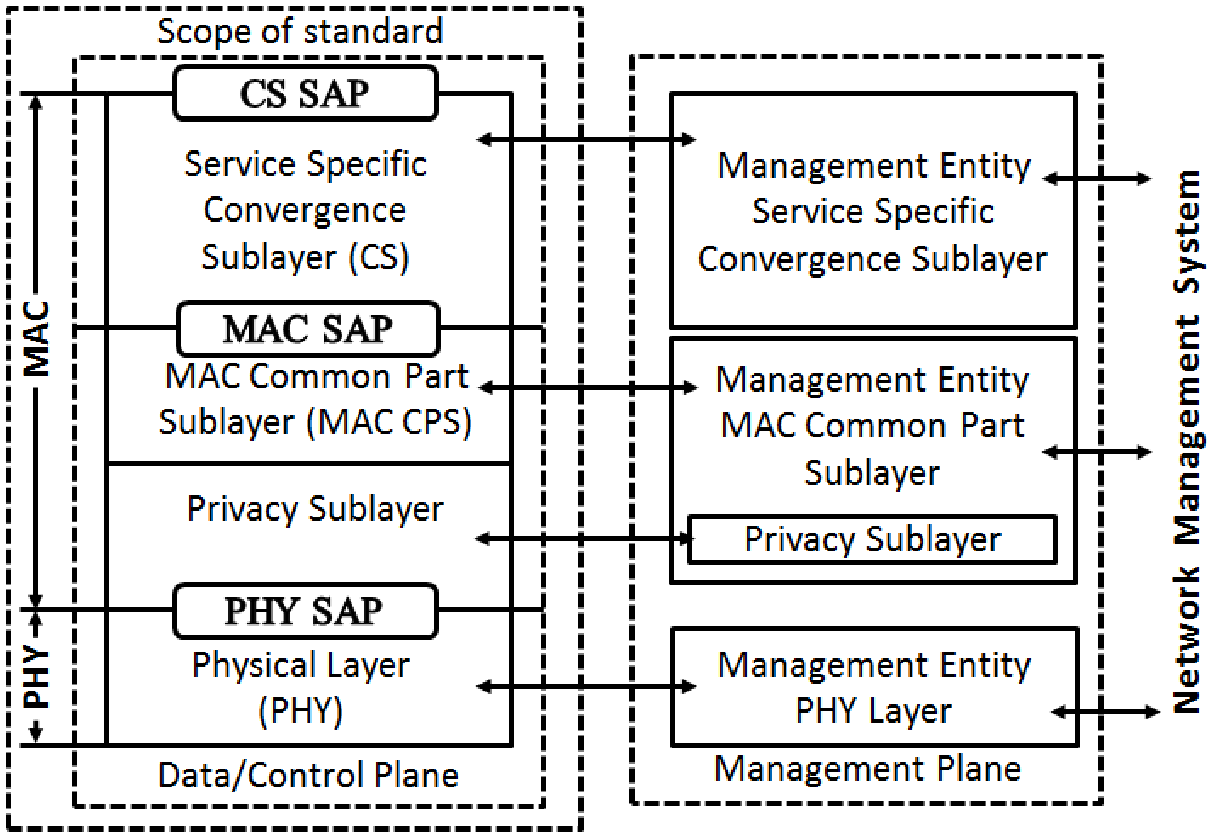


Figure 2.2. IEEE 802.16 reference model [35].

The IEEE 802.16 reference model shown in Figure 2.2 is composed of two layers, namely MAC layer and PHY layer. The MAC layer is composed of three sub-layers, that is, the convergence sublayer (CS), the common part sublayer (CPS), and the security sub-layer. The convergence sub-layer connects the common part sublayer to upper layers. It receives service data units (SDUs) from the upper layer, and classifies them into the right connections, based on their QoS parameters. After the classification of SDUs the data are forwarded to the CPS which is responsible for the following tasks: request the bandwidth and allocate flows to connection, establish a connection, resolve contention, manage QoS, and scheduling. Since this thesis deals with multicast scheduling, MAC and physical layers which perform the scheduling function as shown in Figure 2.2, are considered.

2.2.2. WiMAX Benefits

WiMAX communication technology is used to overcome the limitations of cable use, Digital Subscriber Line (DSL), and WiFi backhaul in the areas where it is difficult to install wired networks [36]. WiMAX can be deployed in remote areas, and in areas where it is expensive and difficult to utilise cables, or where subscribers are low in numbers. The needs of potential users in such areas would thus be satisfied. The WiMAX covers a wide area up to a range of 30 km, while conventional DSL can only cover an area of 5 km from the central office switch [2]. This is why users can access services from the core network at a high speed up to 75 Mbps. Although WiMAX solves the cable problem, wireless networks do not fully solve connectivity problems as the wireless medium has unreliable characteristics. Moreover, the wireless network has a limited spectrum and unpredictable channels that can degrade the data rate [18].

Hence, the numbers mentioned above can only be achieved in the best environment. Mass deployment is expensive when it comes to other wireless access technologies because of the standards required to facilitate the economies of scale [35]. For this, IEEE 802.16 has the following capabilities: it supports NLoS, provides high bandwidth (greater than 10 MHZ) and inherent flexibility. These qualities enhance the ability to deal with the above limitations. In designing WiMAX, the interoperability between WiMAX and other wireless access technologies was taken into consideration [19]. This means that roaming between WiMAX network and other wireless communication technologies is feasible.

Research in [2] proved that WiMAX provides high bandwidth which facilitates the delivery of real-time applications much faster than other technologies. Similarly, LTE. However, its deployment is rare in developing countries and, even where it is found, many users cannot afford it. For this reason, WiMAX technology provides freedom to request and provide applications to the subscriber stations and service providers, respectively. Moreover, mobile WiMAX incites early appearance of mobile applications that deals with the particular needs of mobile internet users. Finally, the IP multimedia subsystem (IMS) support in WiMAX enables a unified deployment and manageable service for subscribers across wired and wireless platforms [2].

2.3. WiMAX Multicasting

2.3.1. Multicasting Technology

In the communication field there are three types of communication. These are unicast, multicast, and broadcast [37].

Unicast is a one-to-one delivery method. Figure 2.3 illustrates the unicast methodology, where destinations request the same content, and the content is delivered individually to the destinations from the source.

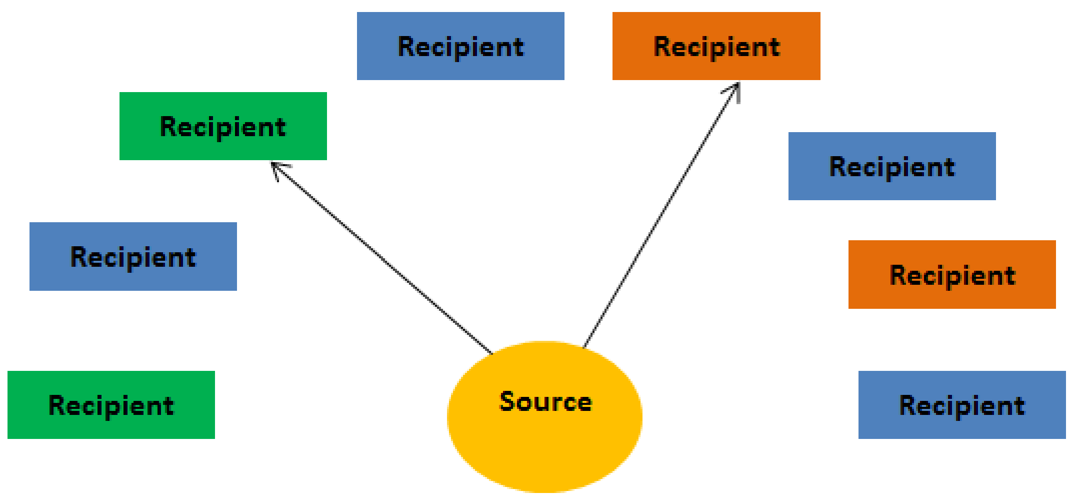


Figure 2.3. Unicast service as one-to-one communication

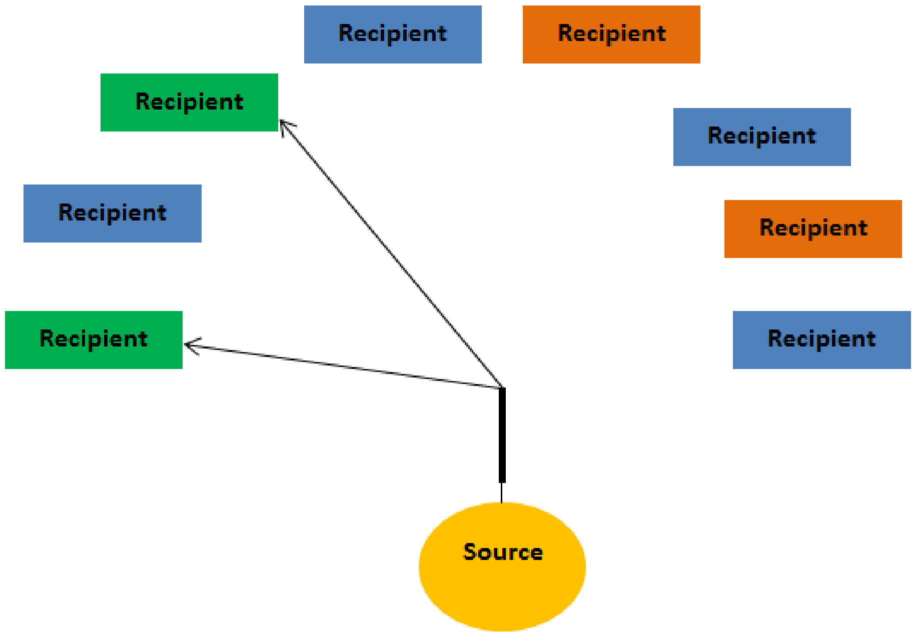


Figure 2.4. Multicast service as one-to-many communications.

Multicast is the transmission from one source to many destinations, where the same content is transmitted to multiple receivers simultaneously [18]. Figure 2.4 illustrates multicast communication methodology. Multicasting is a downlink data service which is used to transmit multicast content such as video and audio streaming, and file sharing to a large population of users simultaneously through a single channel using the same transmission rate from the source without excessive bandwidth consumption.

Multicasting in WiMAX networks can be a PTP, PTM and, Multipoint-To-Multipoint (MTM) scheme. With the PTM and MTM schemes, a single channel is used to broadcast over the entire cell; whereas with the PTP scheme, multicast traffic is duplicated within the radio access network for each user in such a way each user receives multicast traffic on a dedicated channel [37].

In some cases the information may be duplicated within nodes; the duplication of the information is done when this is necessary as it depends on the network topology. PTP and MTM communication schemes are not the concern of this thesis because the nature of this thesis is to analyse PTM communication. One may decide to use PTP communication when there are only a few users in the multicast group. For example, when only one user joins a multicast group, PTP communication applies.

Broadcast is one-to-all communication. Figure 2.5 illustrates the methodology of multicast communication where all destinations receive the transmitted content [18].

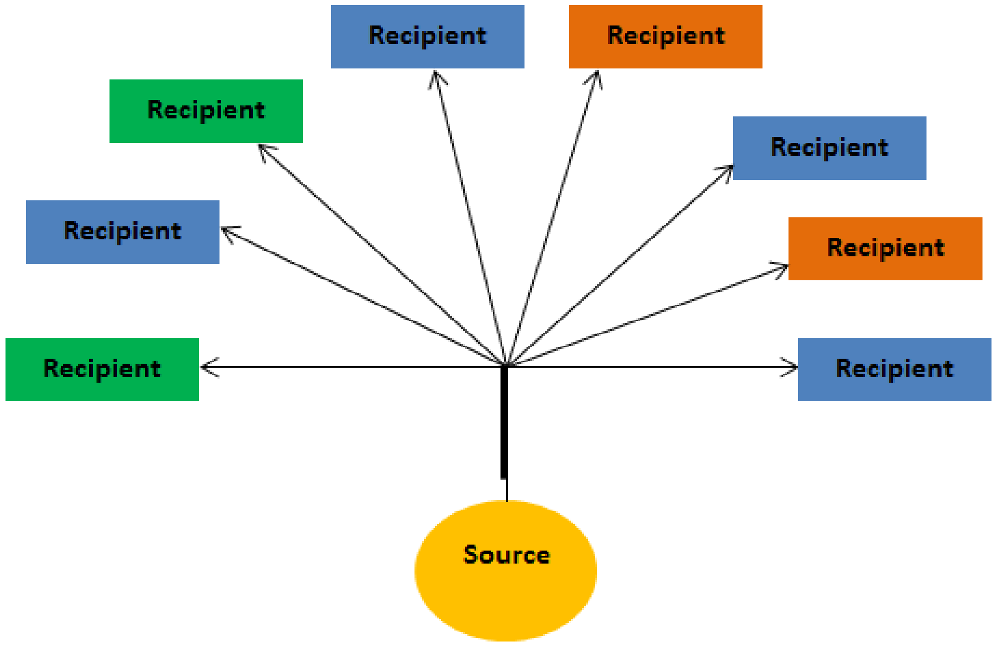


Figure 2.5. Broadcast communication as one-to-all.

The deployment of multicasting in communication field can be performed at different layers as references [37], [38] describe it as follows:

- Multicasting at the application layer
- Multicasting at the network layer
- Multicasting at the physical layer

Multicasting at the application layer means that the common content is transmitted to a group of applications via point-to-point transport. In this way, the data packets replication is performed at the node's end. This would result in less efficiency because unicast communication is always applied to the network layer, for instance, an email with multiple recipients.

Multicasting at the network layer means that the common content is transmitted to users in a group and the duplication of data packets are performed at the network routers; this would optimise the routing for the network by duplicating data packets, but only if this requires different links to reach the destination.

Multicasting at the physical layer means that the common content is sent through physical link. Ethernet Broadcast transmission is a good example of this.

Multicast is best suited for the delivery of multimedia content over wireless networks because it offers flexible QoS to multicast group members. Multicasting transmitted to public internet experiences various problems due to resource potential and QoS maintenance [18]. Two main types of multicast traffic exist such as real-time and reliable multicast [37]. In real-time multicast, the networks simultaneously provide data in real time to multicast group members. This is performed in consideration to any delay and jitter constraints. However, the losses incurred are ignored. In reliable multicast, the network does not take into account the delay constraints, but ensures a reliability guarantee for the transmitted data. This thesis focuses on multicast at network layer since internetwork was involved, and content was to be transmitted to a group of users requesting the same content from different virtual networks. Hence the duplication of data should be performed at the router level.

Third Generation (3G) supports a multicast service through the setup of a single radio channel appropriate to the transport of multicast traffic. These are connected to higher or lower bit-streams with the use of Real-Time Control Protocol (RTCP) [37]. In the wireless networks, multicasting is challenging because of the channel variation and received signal strength variability [39]. Thus in any network system, data delivery can be reliable if they are received correctly. In multicasting service, data can be received reliably if multicast is performed correctly.

Multicasting can be viewed from two aspects according to reference [38]. They are network and application aspects. In the network perspective, the network resources are shared with multiple destinations when the source sends the content simultaneously, using the same channel at a single rate. In this case, the bandwidth is efficiently utilised because initially the same bandwidth multiplies the total number of destinations. Thus, the network resources to be shared can be:

- Bandwidth
- Infrastructure
- Channel
- Radio resources

Multicast addressing is the benefit of multicasting technology where one to multiple destinations are addressed simultaneously, thereby reducing the overheads [38]. Thus, in application perspective, reliable information would be sent to multiple destinations using Forward Error Correction (FEC) and the information could be sent in the same order so that it is easily recovered at destination [38].

Importantly, multicasting is the most useful application when certain applications have to be transmitted to selected groups of users. For example, if users want to access updates of geographical information in their areas such as traffic reports, local news, daily weather forecast, store prices and advertisements of the location-based item, multicasting delivers such information most efficiently. Consequently, the stated information might include FLO™ mobile, forward TV services, Integrated Services Digital Broadcasting Television (ISDB-T) (the International Telecommunication Union (ITU) standard (ITU-RBT B06)) Satellite-Based Mobile TV Services, and Microsoft IPTV [36]. This provides IPTV to homes which are quality applications of multicasting.

However, multicasting can efficiently deliver other types of information to the destinations such as video conferencing and multimedia content. Since many users require the information provided by video conferencing and multimedia, it can be sent to users via a single channel instead of multiple channels. In this case the bandwidth is efficiently used. Hence, results are far more cost effective in speed and information dissemination.

Obviously, WiMAX supports multicasting services which enables a large number of users to receive the same service in its network. Multicasting is an effective technology that is used to send shared multimedia content to a large number of users (such as video, audio, software updates and similar applications) at the same time using a single channel. This results in the efficient use of bandwidth. It would be neither practical nor possible to deploy internet television that uses broadband unicast to multiple laptops in an office because the network bandwidth would quickly be saturated [36]. To provide multicast services in wireless networks, as stated in [18], the following steps are required:

- Content creation
- Scheduling and service-level agreement (SLA) between network operators and intellectual right owners

- Service advertisement registration, which checks for the authentication and authorization
- Media discovery

2.3.2. MBS Technology

The network should be configured as a radio access and backbone infrastructure to provide multicast services over WiMAX network. This is because the content's source is the server and the traffic passes through the router which identifies the destination address and forwards the packets to the destination address. Thus, the multicast router resides on the backbone side [18]. Radio access mode does not have wired infrastructure connected to it. The backbone infrastructure is connected to a wired network through a number of base stations. Although multicasting uses bandwidth resources efficiently, however there is still scarce bandwidth in wireless networks which is limited as the number of users requesting services require high bandwidth increases. This thesis tries to solve the bandwidth problem by using multicast service virtualization which reduces the bandwidth consumption in wireless networks.

Multicast Broadcast Service (MBS) was introduced to improve the optimisation of bandwidth utilisation [40]. MBS can be employed in one base station (BS) or multiple base stations of the same network. Similarly, MBS is a MAC aspect in IEEE 802.16, and it was enhanced to include a compressed group of Dynamic Service Messages (DSx). DSx reduces signalling and the overhead latency involved in setting up multiple MBS flows associated with one MBS zone. This zone is composed of multiple base stations configured with MBS. The group DSx is a new message that utilises the redundancies among service flow attributes for a number of multicast connections. It is also used to generate multiple connections that use a unified and optimised MAC message delivery.

Multicast and broadcast services are methods used to provide the transport of data from a single sender to multiple receivers. Thus, with multicast and broadcast services, the content is delivered at low cost since the content is transmitted to many users at the same time via a single channel. Multicast and Broadcast Service (MBS) are a downlink service which may be coordinated and synchronised across base stations where the multicast services are transmitted from different BSs using Single-Frequency Network (SFN) [6]. For this reason, a multicast connection is assigned to a service flow, where each service flow associated with

MBS has defined QoS characteristics [39]. The same flows are transmitted by all services initiated on any mobile station and they have the same service flow management encodings of the QoS parameters. In this thesis, multicast zones are not considered because only one base station per virtual network was used with multiple flows of different QoS parameters.

In MBS, Broadcast services are free to users who are authorised to have access to a network. When multicast is subscription-based, users are charged for the multicast service [41]. Based on data transmission behaviour, there exist two types of multicast service flow:

- **Static multicast service.** This occurs when the number, mobility, and location of targeted users do not affect data transmission and its configuration parameter.
- **Dynamic multicast service.** This occurs when data transmission and its configuration values change based on the number, location, and mobility of targeted users.

The entities of MBS architecture proposed in [41] are described in Figure 2.6. The architecture is composed of MBS source; CSN which is composed of Multicast Broadcast Service controller (MBSC); NAP is composed of Access Service Providers and Mobile service providers. Comparing the WiMAX architecture with the MBS architecture for mobile WiMAX, the difference is that there is an addition of MBS source and MBSC in the connectivity service network.

MBS was improved and from it the enhanced multicast broadcast service (E-MBS) framework was defined. This has a MAC and a PHY layer that describes the communication between base station and subscriber stations. Enhanced Multicast Broadcast Service MAC (EMBS-MAC) framework functions are described as follows:

- Group configuration
- Transmission mode configuration
- Session management
- Mobility management
- Control signalling

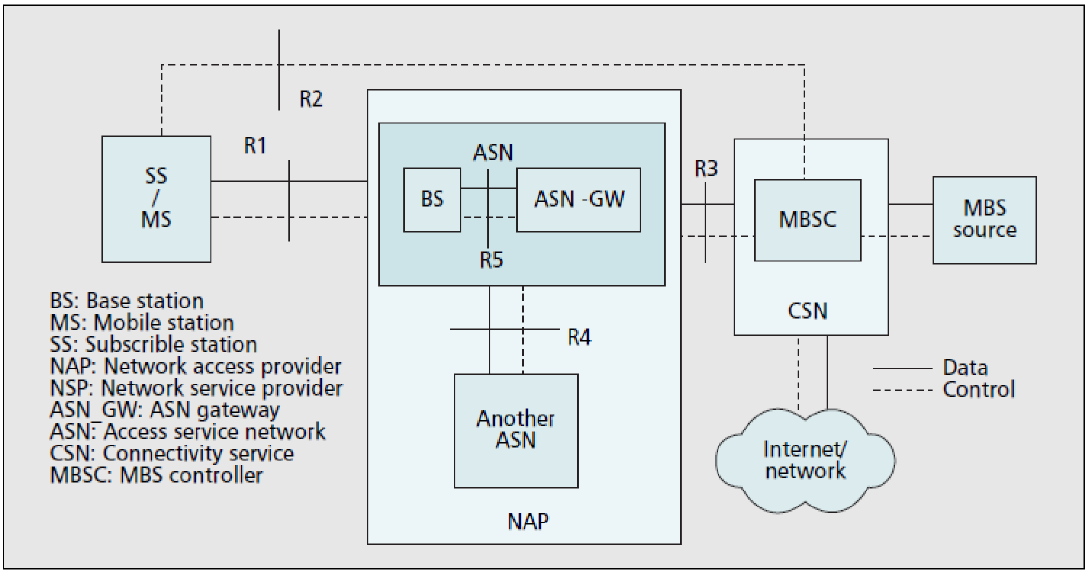


Figure 2.6. MBS architecture for mobile WiMAX [41].

Ongoing research on multicast services technology has achieved a more efficient delivery of multicasting services and bandwidth utilisation. Included in this research is a new architecture of multicasting, that is, Multimedia Multicast Broadcast Services (MCBCS) which has improved the utilisation of bandwidth. The next section introduces the MCBCS technology.

2.3.3. MCBCS Technology

MCBCS is low-cost reliable and secure service in comparison with unicast broadband, and it is a solution to spectrum efficiency maximisation. The previously stated advantages of multicasting were not related to MCBCS, which have been designed specifically for wireless networks - in particular WiMAX network [41].

MCBCS's effective technology gives mobile WiMAX an advantage over all other wireless networks. Its system delivers real-time, high quality and interactive multimedia content to users. The operational modes of the multicast and broadcast services are streaming and download modes. In streaming mode, data flow continuously in the form of a stream. Consequently, the download mode ensures the reliability of the data delivery which is transformed into binary data. Accordingly, reference [36] states that the base station is to identify mobile stations so that the multicast service knows which mobile station is entitled to which multicast content. Further, a given multicast service is assigned a Connection Identifier (CID), and the assigned CID value is uniform for all subscriber stations who receive the same multicast content. This is why the offered QoS and traffic characteristics are the same for all subscriber stations that receive the same multicast content through a single channel with the same channel conditions.

Multicast services can be transmitted through Internet Group Management Protocol version 3 (IGMPV3) or version 2 (IGMPV2) which is the most commonly used method nowadays. When network delivers the video on demand services, Real Time Protocol (RTP) or Real Time Streaming Protocol (RTSP) (RFC 2326) are used [36]. Thus, WiMAX offers excellent control capabilities that facilitate the deployment of multicasting overlay networks. This is done where multiple services are expanded over WiMAX networks with traditional services [36]. As a result, a new range of networking capabilities consistent with the requirements of MCBCS classes of services was introduced. To this end, network operators are interested in delivering content at a low price in PTM mode, using minimal network resources (single channel). Basically, MCBCS is a downlink data service with the purpose of sending content such as video streaming, audio streaming and file sharing to a large population of users. Broadcast services are delivered to users free of charge while multicast services are subscription-based.

The WiMAX functional architecture allows logical separation of access, connectivity and application services. WiMAX architecture is divided into two parts: radio access and core networks. Figure 2.7 describes the content distribution with MCBCS technique: the content providers of application services create and deliver the multimedia content to a multicast server located at the side of a network service provider. The network service provider delivers content to the suitable NAP and performs the management of service provision.

The multicast broadcast content is then sent via multiple channels to a geographical location, known as a multicast transmission zone. Each such MBS zone contains single or multiple base stations. The configuration of multicast broadcast zones may overlap depending on the service area targeted for the content of each channel or multicast group. Data transportation from multicast server to multicast broadcast zone is managed over IP multicasting. For example, when a mobile station changes from one base station to the another within the same multicast broadcast zone, the mobile station may need minimal interaction, or it may not need to interact at all with the base station or the network with the changing channel [41].

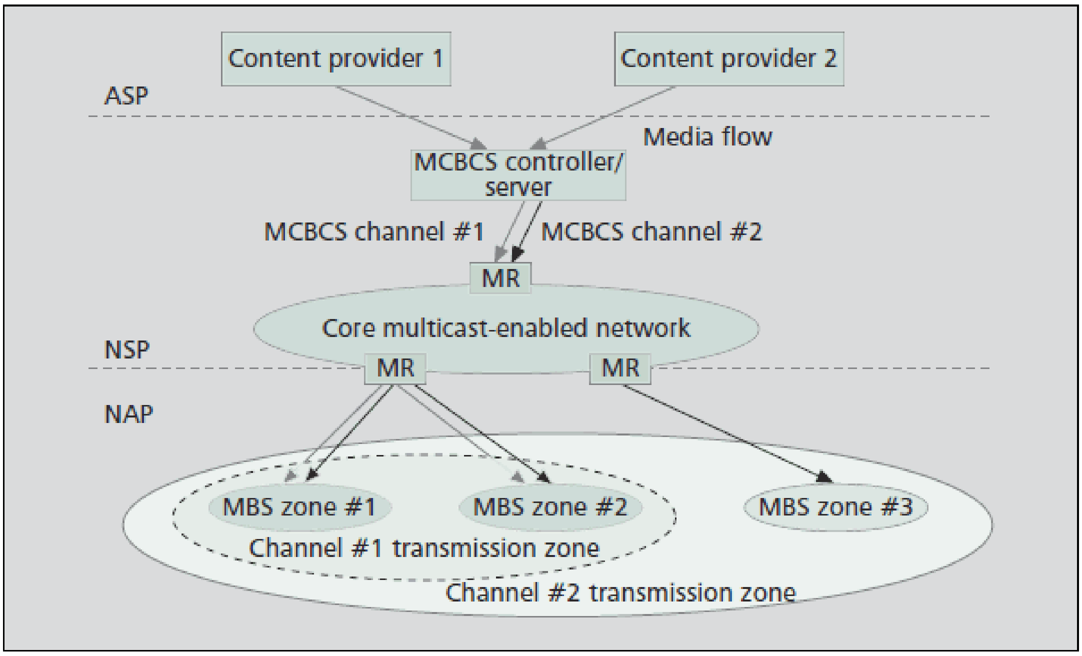


Figure 2.7. Content distribution scheme in ASP/NSP/NAP stack [41].

A base station can offer the mobile station the MBS content in its local area within its coverage range independently of other base stations. This type of configuration is an MBS zone. It contains a single BS only. MCBCS is managed in such a way that different BSs in an MBS zone are coordinated and synchronised to transmit MBS content to different MS located at different BSs. Figure 2.8 describes functional entities of MCBCS/WiMAX network architecture. This architecture has three main parts, namely the CSN, ASN, and the MS. The ASN is composed of two entities: BS and ASN Gateway (ASNGW). These are mandatory entities of WiMAX networks. When MCBCS is considered, more functional entities may be required to enable WiMAX to offer multicast and broadcast services.

The following are the roles of MCBCS in CSN:

- **MCBCS Controller/Server**. This is a logical network entity which may also be a physical entity. It manages the application layer security and services of MCBCS in CSN.
- **Authentication, Authorization, Accounting/Path Flow** (**AAA/PF)** enable MS to receive specific services from MCBCS.
- **Database profile for the subscriber**. This stores the users' profiles.

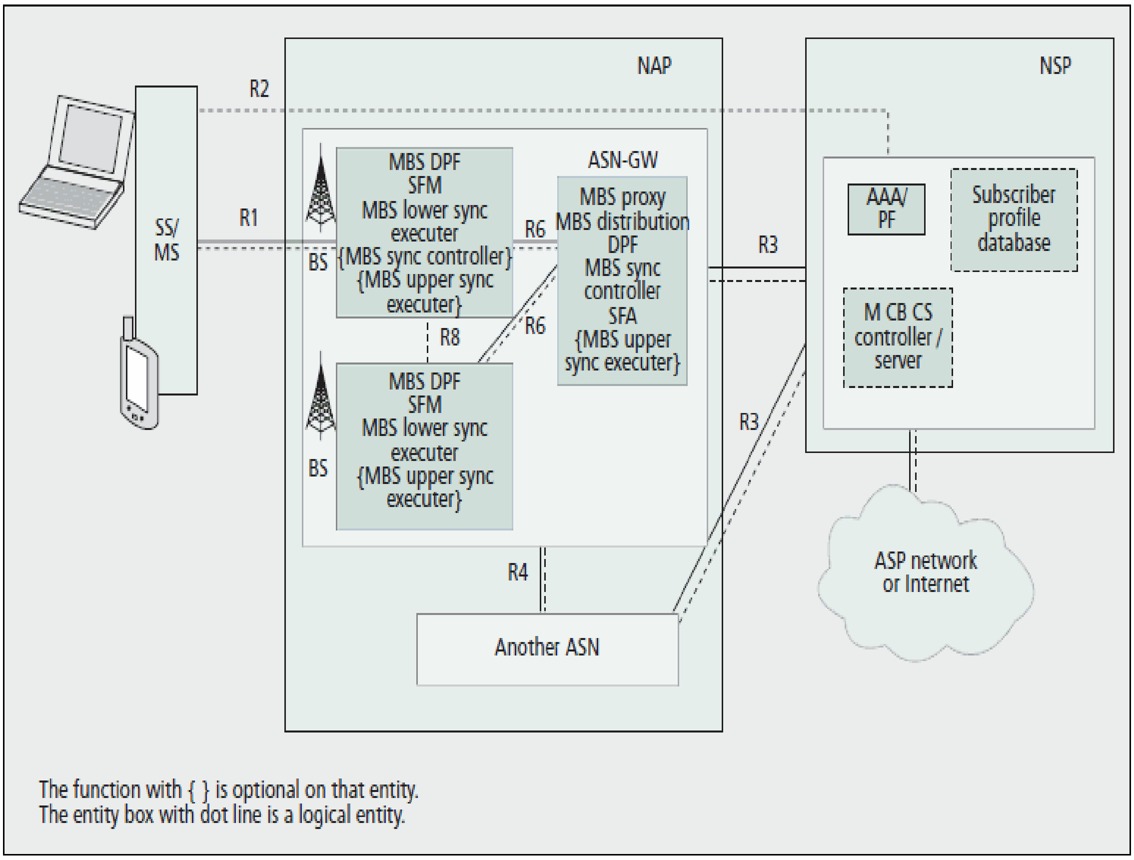


Figure 2.8. MCBCS/WiMAX network reference model [41].

NAP functional entities are as follows:

- **MBS Proxy**. In an MBS zone, MBS proxy performs the coordination and session management between CSN and ASN. It triggers the distribution of Data Path Functions (DPF) of MBS and controls paths on which data will be distributed. It also allocates radio resource parameters such as Multicast Connection Identifier (MCID) to MBS service flow and coordinates one or more MBS zones.
- Service Flow Authorization (**SFA)**. An MBS proxy communicates with the SAF to acquire the updated information on service requirements.

MCBCS that have been designed for WiMAX technology can deliver common content to many users in two modes: multicast mode and broadcast mode. However, broadcast mode is not the concern of this thesis. This thesis focuses on virtualization of multicast services in WiMAX networks, where multicast content is delivered over a single virtual network instead of being delivered over multiple virtual networks. In other words, the advantage of multicasting is the goal of this dissertation. There is a dynamic joining of users to a multicast group and IP session and the number of users in MCBCS. The connection can be monitored so that the system decides which transmission mode to use. MCBCS was designed to provide regional or national multimedia content to users who belong to the same large network where cell sizes, frequency reuse and the mobility of the users vary greatly [18].

MCBCS data transmission over WiMAX is a technology that lowers spectrum cost more than other wireless broadband technologies. This applies through optimisation of spectrum use. Thus, it enables network operators to offer a new set of bandwidth-heavy subscriber services. The MCBCS is cost-effective, and it can offer high-quality services to users and bandwidth-heavy content. The MCBCS benefits both network operators and subscribers in today's market. The MCBCS in WiMAX networks offers the following services to subscribers as they are listed in [42] :

- Live mobile or local IPTV which may be distributed on local, regional or national multicasting; live operations, such as sports, music and news, would be transmitted over five to ten channels at low bandwidth.
- Video on demand application can be delivered through MCBCS technology, where video content can be uploaded during idle time of mobile network devices to playback in peak or non-peak time.
- MCBS support the application of maintenance and upgrade wherever firmware and other mobile devices software operate.
- Geographically-bound events provide support for MCBCS through delivery or multicasting of local or regional information such as sports, news, advertisements and similar related services.

MCBCS support other applications such as messaging, entertainment and public safety. MCBCS lowers the spectrum cost considerably when extreme fast data transfer speed is enabled [42], as WiMAX maintains the average spectrum. The MCBCS/WiMAX optimises the utilisation of the bandwidth where network operators are activated to offer different services to distinct multicast groups. MCBCS over WiMAX gives power and freedom to network operators to become flexible. Network operators should ensure that the subscribers receive what they pay for. This is because in MCBCS, subscribers in different locations may join more than one multicast service and it will be challenging to control the charging policy.

Fortunately network virtualization enables the use of a virtual network manager to determine which user is subscribed to which multicast service.

MCBCS improves security through the activation of content encryption on the application level of the system and infrastructure level network protection [42], because it prevents fraud and other network-related disagreements. This guarantees unbeatable security management. It equally improves the quality of service as the spectrum is efficiently used. Thus, since network operators can simultaniously transmit large amounts of data using MCBCS technology, the quality of the received data is improved.

Table 2.2. Multicasting issues and various pricing solutions [43].

Multicast issues	Existing solution for pricing
Multicast services charge in wireless networks.	Flat-rate
	Transmitted number of packets
	Multicast group members number
	Multicast session duration
	Link type, distance, and congestion
	Multicast session duration, multicast group members, and packets numbers
	Time sensitive
Revenue distribution among various service providers	Packets distance ratio travelled in individual networks
	Packet and copies number in a single network
	Number of used routers
	Network customer numbers in session
	A hybrid of the above stated factors

2.3.4. Multicasting Applications

Multicasting can be deployed for group communication. Some multicasting applications include commercial applications such as mobile auctions. These types of applications require secure connectivity and reliable wireless multicast. On the other hand, multicasting can be used in military operations for sending secured information to users, planes, and other partners. These types of applications require minimal delay with a secured and wireless network that reliably caters for multicast service provision. Thus, viewing quality pictures with high bandwidth benefits distance learning users. However many issues remain within wired and wireless multicast application, as illustrated by Table 2.2.

2.4. Review of Multicasting Techniques

2.4.1. Multicast scheduling

The selection of transmission rate from a multicast group still prevents the multicast application from achieving an outstanding performance. Also, the allocation of network resources to multicast group, in order to ensure a better QoS performance from users, has a negative effect on multicasting. For this reason, three metrics should be considered to evaluate the performance of multicast services: throughput, reliability and fairness.

Previous research extensively exploited a fixed and low transmission rate of multicast services. This technique enabled distant users from base stations to benefit from services. However, this multicasting only provided users within the proximity of the base station high data rates, and users located at the far end of a base station unfortunately received with a limited throughput [26]. Besides, if the transmission rate was reduced, it provoked a negative impact on users with good channel conditions.

Further to that, research in this area aimed to achieve high throughput and optimum performance fairness. Thus, scholars proposed a scheme to achieve a proportional fair scheduling whereby the dynamic selection of transmission rate and multicast group was the result of a proportionally fair decision. That was to avoid relying on group members with critical channel conditions. As stated earlier, the aim of this research is to use multicast service virtualization for the efficient use of bandwidth in wireless networks for better network performance. This involves virtualization which enables the sharing of services through multiple virtual networks. It is done by network selection that decides the virtual network on which to deliver the multicast flow, and also by providing better QoS to users through scheduling of multicast service within a virtual network that considers the delay of multicast group members. This was not done in the literature.

On the other hand, the inter-group proportional fairness scheme was proposed in [27]. The BS base station selects the transmission rate and the multicast group to maximise the logarithm summation of each multicast group throughput. The two schemes involve two proportionally fair scheduling algorithms that consider channel conditions. The two proposed algorithms are Inter-Proportional Fairness (IPF) and Multicast Proportional Fairness (MPF). These can adapt to a dynamic channel state in cellular data networks that use time division multiplexing. Both the above schemes led to a good adjustment between fairness and throughput. However, the negative impact of bad channel state on the achieved throughput was ignored. Alternatively, a fair and stable resource allocation scheme for multicast sessions was recommended. This resource allocation, applied to multi-rate transmission, scheduled virtual traffic. Then virtual traffic moving in a reverse direction from the receiver to the transmitter was proposed [28] in order to control delays in the wireless network. Consequently, an optimal multi-rate multicast was established.

A Max-Sum algorithm, combining the small data packets to form a bigger data packet for efficient use of bandwidth, was proposed [32]. The algorithm was used only to schedule multicast video streaming in a single network and to select the multicast group, but did not consider the multicast group transmission rate. This thesis will solve the QoS problem by using scheduling of multicast service within virtual networks which consider an individual user's QoS demand.

Thus, wireless networks characteristics may trigger a significant difference in channel conditions of users who subscribe to the same multicast service. Obviously, the proposed algorithm satisfies users who experience different channel conditions. For this reason, a cross-layer framework for downlink scheduling of multimedia traffic was suggested in [44]. The framework simultaneously performed the cross-layers adaptation from protocol stacks on source coding, prioritisation flow queuing, and scheduling. The wireless link variations, queue fluctuations, and reception diversities were also considered. The proposed framework is feasible and efficient. Moreover, the proposed scheduler improved performance on delay, throughput and fairness. However, the two schemes did not consider the group selection. This only led to the selection of multicast transmission rate, but QoS for different users was not considered. The contribution of this research provides multicast scheduling within the virtual network by providing QoS to individual users. This was not considered in the previous studies.

The above gap revealed the proposal of channel efficiency factor as a novel metric which is based on the service level agreement scheme [45]. This uses channel state information from users and congestion conditions of the base station and determines the allocation of bandwidth to multicast groups. The proposed scheme improves the network throughput and channel blocking probability. Previously, QoS was not provided because only channel state information and base station congestion were considered for bandwidth allocation.

As a solution to the above system, a utility-based resource allocation scheme was used. This operates with adaptive modulation and coding through encoding. Each video stream is adopted at different layers [46]. The scheme dynamically adapts layers for each user. This is based on users' channel conditions and the available bandwidth to maximise and fully guarantee utility and system fairness. In this regard, the definition of a utility that works for video streaming remains unanswered.

A video content coding scheme at multicast layer was proposed to ensure a successful transmission of video traffic in WiMAX networks through adaptive modulation [47]. This ensures a low rate to each received signal and an enhancement layer for the receivers which cannot recover the signal. In [48] an algorithm which divides the multicast data into the data of basic layer and the data of enhancement layer was allocated to the sub-channel and power. This was done to maximise the total network throughput based on the total power. At the same time, it ensures minimum required transmission rate for both the unicast and multicast flow schemes. The paper articulated described sub-channel and power allocation while the bandwidth, a crucial issue in wireless networks, was ignored. The above scheme on the basic layer and enhancement layer argued about the transmission rate selection. However, the group selection was also ignored.

Further, a multi-rate adaptation controller was designed in [34]. It is a multicast-rate controller that supports a multi-rate multicast transmission, within the constraints of multicast receivers of long propagation delay feedback. This releases the unresponsiveness of multicast flow that is caused by long propagation delays from receivers. As a result good scalability, stable buffer occupancy, fast response to users, and high link utilisation reveal outstanding achievements. In using receiver's rate, the network has determined multicast source rate. In this case the transmission rate changes in time, but each multicast group has its own transmission rate, that is, if users belong to the same group, they receive the same multicast transmission rate. Only receiver's rate has been used to decide on the transmission rate. This does not provide QoS to users. This thesis tries to solve this problem by selecting the multicast group rate and taking into account the individual user's QoS.

Group division into subgroups method was adopted to improve the network resource utilisation efficiency. Link adaptation technique, based on the dynamic selection of modulation and coding scheme that account for the received channel state information of each multicast group member at the base station, was proposed [29], [30], [31]. The idea was to split multicast groups into subgroups according to their perceived channel conditions for the efficient delivery of multicast services. However, that did not solve the QoS problems.

In response to the above issue, the framework of maximising a unified utility was tested. Experimentation of users with the same path losses and those with different path losses was done [49]. Results proved that when more than one subgroup was tested, each group displayed their transmission rate. Convincingly, the transmission rate for users with the same path losses tallied, while transmission rate for users with different pass losses differed. This theoretical analysis has proved that the multicast scheme ranked highest because various throughput-fairness requirements were satisfied in both scenarios. Though transmission rate was provided to a small group of users, this research did not consider the individual multicast group member's QoS in determining the transmission rate of the multicast group. The only performance metric considered is the data rate. Delay and jitter have been ignored and consequently this thesis capitalises on individual multicast group member's QoS, such as delay and jitter, to provide multicast service with better QoS to most users in a multicast group.

A strength-based subcarrier selection algorithm for users was developed in [50]. The algorithm uses the knowledge of subcarrier to offer better QoS to improve network throughput and reduce the error rate. The study considered subcarrier domain and the objectives were not focused on bandwidth efficiency use. However research activities in [51] proposed a reception rate tracking that can control the rate at which data of each subcarrier is received, along with the Forward Error Corrections (FEC). Similarly, it determines modulation code-rate and coding scheme for robust data transmission and eliminates losses to achieve efficient resource use.

A cooperative multicast scheduling scheme, for exploiting the multi-channel diversity across different multicast groups and users' cooperation among group members, was proposed in [52]. The proposed scheme uses multicast group members with good channel conditions to relay multicast content to other multicast group members with poor channel conditions. Hence, this achieves more efficient and reliable multicast transmission and higher throughput than the existing multicast schemes for subscriber stations in both good and bad channel conditions. Also, it offers good performance based on normalisation of the relative channel condition of each multicast group. However, individual QoS multicast group members were not considered for providing content to multicast group members with requested QoS.

Bandwidth allocation scheme that supports scalable video multicast in WiMAX relay network with limited bandwidth availability constraints was proposed in [53]. The bandwidth allocation scheme can effectively achieve good performances with different parameter settings by avoiding the redundant bandwidth allocation. However, since this has not been efficiently achieved, there is another way to improve it. When multiple users involved in networks from the same or different networks request the same content, this content will be delivered over their respective networks. Thus optimal network selection can minimise this bandwidth to deliver multicast content.

The adaptive modulation approach was used and the multicast rate was chosen depending on multicast video layer, subscriber stations' group and available symbols. This resulted in rate optimisation actualization. Although the work was dealing with rate optimisation, network performance was not evaluated to check whether the chosen rate was the best. The QoS problem was also not considered; users today need to receive improved QoS [54]. Figure 2.9 illustrates MAC layer with multicast group scheduling. It shows two multicast groups, and each of the two groups receives multicast content from the base station. MAC layer has the role of classifying packets, based on their QoS parameters, and selecting the flows to be transmitted first - depending on their priority and QoS characteristics. There is also a scheduling algorithm at the multicast group level which decides which multicast group is to be given priority.

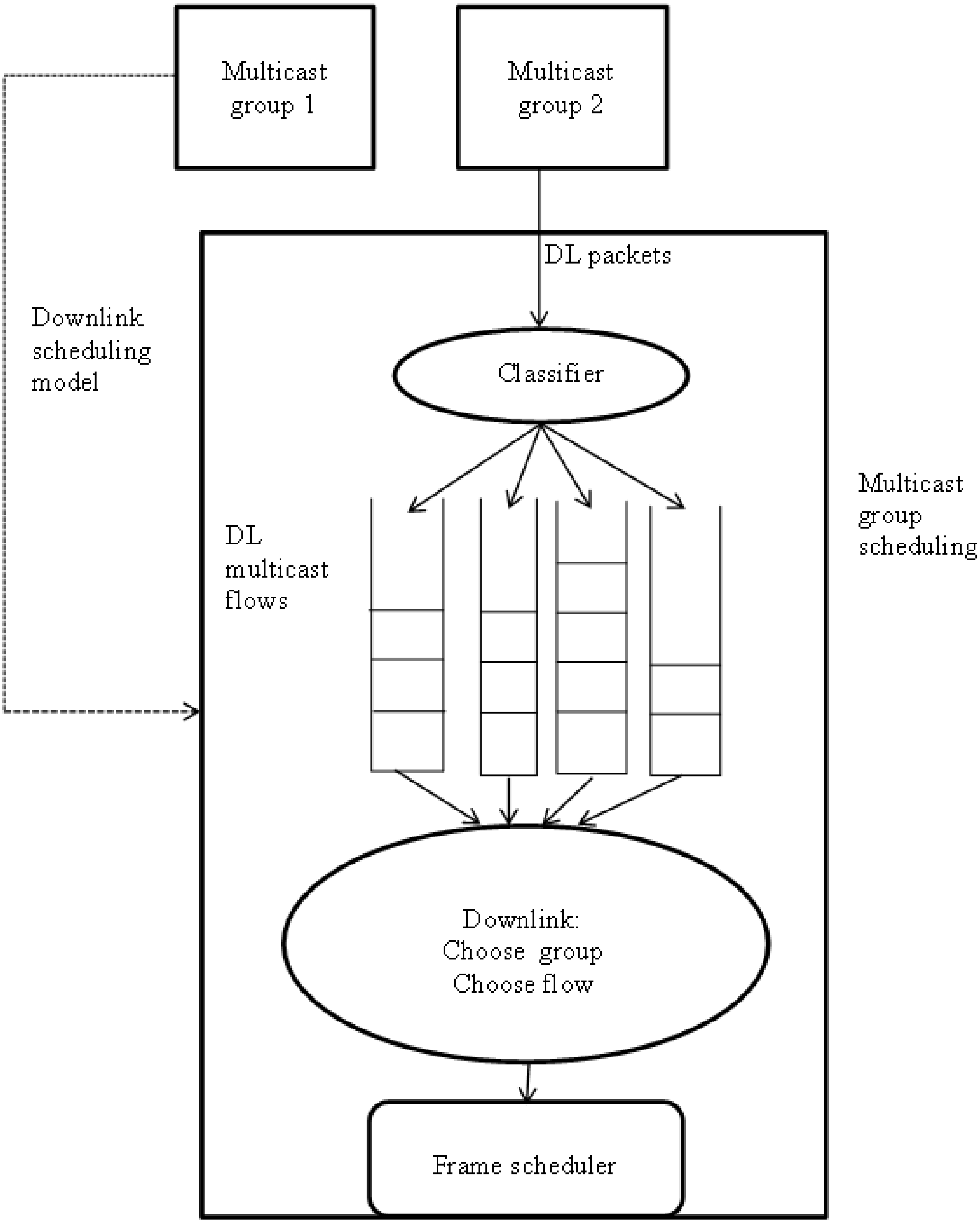


Figure 2.9. MAC layer with multicast group scheduling.

The multicasting techniques stated above are related to scheduling techniques, and the differences between these techniques are highlighted in Table 2.3.

Table 2.3 Comparison of multicasting scheduling techniques.

Approaches	Used techniques	Advantages	Limitations
Fixed single transmission rate [30]	-Use fixed low for transmission rate of multicast group. -Scheduling based on channel users' condition.	-The user located far away from the base station can be serviced. -It achieves high throughput and optimum performance fairness.	-The users located at the edge of a cell receive with limited throughput. -A detrimental effect occurs on the users having high channel quality when the transmission rate is reduced.
Adaptive single transmission rate [26]	-Dynamic selection of transmission rate and the multicast group. -Proportional fair rate selection based on decision. -No channel condition considered.	-Proportional fair scheduling achievement.	- Users with worst channel conditions may not receive data.
Adaptive single transmission rate [27]	-Adaptive transmission rate selection. -Channel condition which changes with the function of time was considered.	-Achieve and optimal fairness and throughput.	-The negative effect of bad channel state on the achieved throughput was not taken into consideration.
Multi-rate transmission [28]	-Multi-rate transmission to schedule virtual traffic which moves in reverse direction from the receiver to the transmitter. -Delay for optimising the transmission rate was considered.	-Achieve optimal solution for multi-rate multicast.	-No consideration of channel condition. -No network throughput optimisation. -Lack of fairness.
Multicast group scheduling [32]	-A Max-Sum algorithm that combines the small packets together to form a bigger packet. -No consideration of channel condition. No maximisation of throughput. -No transmission rate selection.	-To achieve efficient use of the bandwidth.	-Network throughput was not maximised. -Lack of fairness.
Dynamic transmission rate [27]	-Dynamic transmission rate. -Proportional fair scheduling. -Channel condition was considered.	Achieve proportional fair scheduling.	No network throughput maximisation.

Approaches	Used techniques	Advantages	Limitations
Multimedia traffic scheduling [44]	-Adaptation of source coding, scheduling, prioritisation based. -Channel condition, queue fluctuation and reception diversities. -No consideration of rate and group selection.	-Performance improvement on delay, throughput and fairness.	-The work was not clear on how they achieved their objectives. -The QoS of each used to optimise QoS of a multicast group was not considered.
Multicast group bandwidth allocation [45]	-Use of a channel efficiency factor as a novel metric based on the service level agreement scheme. -Channel state condition from user. -Consideration of congestion condition of the base station.	-Improvement of network throughput and channel blocking probability.	-QoS was not considered. -No efficient use of bandwidth because all the multicast groups are scheduled at the same time.
Multicast sub-groups [29], [30], [31], [49]	-Link adaptation technique based dynamic selection of the modulation and coding scheme. - Sub-groups formation based on channel condition of mobile stations	-Improve network resource utilisation efficiency. -Throughput-fairness requirements were satisfied.	-No individual QoS was considered. -Delay and jitter were left behind.
Subcarrier strength based selection algorithm [50]	-Use of knowledge of subcarrier.	-Network throughput improvement and error rate reduction.	-No policy on efficient utilisation of bandwidth. -No consideration of channel condition.
Reception rate-tracking. Transmissio n rate selection [51]	-Reception rate-tracking that controls the rate. -No consideration of channel condition. -Only feedback of the received rate was used to determine the coding rate and modulation scheme.	-Achieves an efficient utilisation of resources.	-Throughput, delay, and jitter were not taken into consideration. -No multicast group scheduling.
Adaptive modulation approach based on layers [54]	-Multicast rate selection is based on the multicast video layer, subscriber stations' group and available symbols. -No consideration of channel condition to select the transmission rate.	Rate optimisation.	-No network performance evaluation. -The QoS problem was not considered.

In all the above mentioned techniques, the QoS of users was not taken into consideration; the research focused only on the rate selection and the maximum achieved throughput and fairness of group scheduling based on channel condition of users. However, this thesis considers the individual user's QoS demand to perform optimum scheduling and rate selection in order to satisfy many users in a multicast group.

2.4.2. Network selection in cooperative networks

The bandwidth problem in wireless networks persists because of the increase in the number of users requesting content with high bandwidth. Thus the objective of this research is to find a solution to such problems which exist specifically in heterogeneous networks. The previous section discussed multicasting services; this is one of the solutions, but it cannot fully solve the problem which persists when multicast services are provisioned over heterogeneous networks where the cooperation of access networks exist. In addition, users requesting the multicast content can receive the content by invoking the network selection method to decide on which networks the multicast content is to be delivered. The research work done in this context did not consider the most efficient use of the bandwidth that enables users requesting the same content to receive through a single network. To achieve this, network virtualization was invoked to allow multiple virtual networks sharing the same infrastructure and this also enabled the multicast group members to receive their multicast content through a single virtual network. The following are related studies on the selection of heterogeneous networks.

A study on purchasing methods where the content provider employs the network coded multicast media delivery mechanism is used in [55]. The methods take into account future certainty of customer demand. It is the role of the content provider to decide on capacity provisions according to its market history, and the pattern of customers' resource use. The multicast media delivery mechanism has reduced high costs charged by content providers when they use more resources in SLA than agreed upon. They have predicted network capacity in order to purchase what they can use. This thesis built on those research studies, as their objective is to allocate network resources to content providers. This is done by selecting the network on which to deliver the user content, and more than one network can be chosen to deliver content of users belonging to the same multicast group. In this thesis, more than one network operator is considered and the content will be allocated to networks according to the developed model. The focus of this thesis is to improve the problem of bandwidth use while in research work [55] the cost for content providers was considered in order to use network resources efficiently. Similarly this thesis considers the overall scenario where all network providers determine which network they should deliver the content in order to use the bandwidth and improve network performance efficiency.

A network entity with an easy handover and a network selection scheme was proposed in [56]. This provided improved handover regarding packet loss rate, throughput, handover delay, cell load, bandwidth usage, and peak signal-to-noise ratio. The network selection was performed in heterogeneous networks. The selection was based on handover criteria where a lower loaded network is selected. The same flow can be transmitted to multiple networks which will always consume more bandwidth from cooperative networks. This thesis applies a heterogeneous network approach in the context of multiple networks sharing bandwidth resources. Similarly, it selects the network where the multicast flow is to be delivered. Thus, a multicast flow cannot be delivered to more than one network to reduce the bandwidth consumption.

Load balancing was considered to form multicast groups and select the network [20]. This approach has led to the improvement of network resource utilisation and QoS of users. The network delivers the multicast content to a group member regardless of efficient bandwidth utilisation, however, based on the network offering the best channel to the multicast group member. Hence, the same content can be delivered through multiple networks, and this is still an inefficient way of applying bandwidth. This is why this thesis tries to set up the network selection approach which delivers the multicast content through a single virtual network to use the bandwidth efficiently.

A converged architecture which integrates LTE and DVB-H together was proposed [57]. This research solves the handover problems while moving from one network to the other and will improve the radio resource efficiency and service quality. The selection of the network may be based on the number of users who need broadcast/multicast service, received signal-to-noise ratio (SNR) of User Equipment (UE), capital expenditure (CAPEX), and operating expenses (OPEX). This architecture offers service providers the ability to set up various scenarios to make converged architecture for broadcast/multicast service. The integrated architecture supports handover from one network to the other.

An efficient mechanism for bandwidth utilisation of multicast services in heterogeneous networks was developed in [58]. Adaptive wireless technology and cell selection for each mobile station to join the multicast group was carried out based on the multicast tree. This technology does not solve the bandwidth problems fully since the cell and the technology from which multicast content is delivered to multicast group is initiated by a mobile station. This implies that similar content may be delivered to multiple access technologies and multiple cells. This is not an efficient method for bandwidth management because there is a possibility of delivering the content through a single virtual network instead of delivering the same content through multiple virtual networks. Thus, it is an inefficient method of bandwidth management.

Reference [59] proposed a vertical handover policy for multicast resource management in heterogeneous networks. A solution that provides feasible and ubiquitous support for multicast/broadcast service on heterogeneous accesses was proposed. This technique efficiently reduces the overall power consumption. The study discusses how multicast broadcast services can bear heterogeneous networks. Equally, the research discusses the handover technique to reduce power consumption. However, the research did not analyse efficient use of bandwidth. This reveals a major gap in wireless networks, especially for multimedia services which are transmitted using multicast communication technique. Thus, the thesis addresses the methods of improving the efficient use of bandwidth by using virtualization which enables the delivery of multicast content through a single virtual network.

The work in [3] developed a new resource management framework which schedules and selects an appropriate radio access technology for the delivery of multicast content for each multicast group based on the network, channel conditions and time-varying. The framework ensures efficient utilisation of bandwidth resources and supports the provision of QoS guarantees. The work maximised the network throughput and cost service delivery. The improvement of efficient bandwidth utilisation was considered. Though this study was not the concern of multicast service, the content delivery of the data packet was transmitted through a single network which does not efficiently use the bandwidth, and this thesis seeks to solve this problem.

The study optimises the portion of users in a time slot to minimise delay. This was done in heterogeneous networks on a single network. In heterogeneous networks, chosing to which network to deliver the content depends on whether SNR from each subscriber station is available to the base station. Thus, the selected network for the multicast group member should be transmitted via more than one network since subscribers may need the same content of multiple networks, and the SNR of the subscriber station may perform well in any network [60].

GAP was used in the selection of an appropriate wireless network for each user by utilising the dynamic network status information; QoS being offered by networks and user preferences [61]. The study in [62] has used generalized assignment problems to model the radio resource allocation and Integer Linear Programing (ILP) which gives the exact optimal resource allocation solution as well as the maximum performance in a reasonable time. The resource assignment algorithm is formulated as a generalized assignment problem which maximises the overall profit of mobile nodes studied regarding power consumption and Received Signal Strength (RSS). The GAP formulation considered requested data rate and the limited capacity of networks. Branch and Bound was used to solve the GAP problem [63].

In this study, the flow allocation problem model was formulated as a GAP problem, and MILP was used to find the exact optimal flow allocation solution as well as the maximum throughput performance in reasonable and high execution time. The literature concludes that GAP can be used for flow allocation problems and this is why, in this thesis, GAP is used. The GAP model involves flow rate and network capacities for flow allocation problems. This is similar to the network selection problem.

Surely, GAP has been chosen because it was used in similar works such as heterogeneous network for network selection. Here, WiMAX network is among the wireless networks to assign the network resources to a set of users. This study is different from previous research in heterogeneous networks. It does not compare methods used to perform network selection but considers the problem of scarcity of bandwidth in wireless networks and how these problems can be solved using GAP formulation. Table 2.4 gives a brief overview of the differences between various techniques of network selection of multicast traffic in heterogeneous networks.

The above techniques did not consider the interchangeable multicast services between networks. The studies did not support those users who belong to different networks and request the same content to receive content from a single network on a single channel. These techniques were discussed for the interchange of multicast content with multicast group members who belong to different networks. Accordingly, heterogeneous networks involve multiple access network technologies. These create the analogy of multiple WiMAX networks that share network resources for efficient bandwidth utilisation.

Table 2.4. Comparison of network selection techniques in multiple networks.

Approach	**Used techniques**	**Advantages**	**Limitations**
Network capacity prediction [55]	-The content provider determines capacity provisions based on its market history and the status of customers' resources used patterns. -The methods take into consideration future certainty of customer.	-Reduce high cost charged by content providers when they use much resources of what they have agreed in SLA.	-Bandwidth is not efficiently used.
Handover and a network selection [56]	-The network selection was based on handover criteria where lower loaded network was selected.	-Improves handover packet loss rate, throughput, delay, cell load, bandwidth usage, and peak signal-to-noise ratio.	-Efficient bandwidth utilisation policy is not clear.
Multicast group formation and network selection [20]	-The multicast content is delivered to a group member through the network offering the best channel to it and also based on load balancing.	-Achieve network resource utilisation and QoS of users.	-No policy for efficient bandwidth utilisation.

Approach	Used techniques	Advantages	Limitations
Network selection [57]	-The network selection is based on the • number of users • users received signal-to-noise ratio (SNR) • capital expenditure (CAPEX) • operating expenses (OPEX)	-The integrated architecture supports the handover from LTE to DVB or vice versa.	-The converged architecture operates to improve the radio resource efficiency and Service quality.
Cell and wireless technology selection [58]	-Multicast tree-based cell selection.	-Utilise bandwidth efficiently.	-Does not fully solve bandwidth utilisation.
Cell selection. A vertical handover policy [59]	-The handover which takes power into consideration was done.	-Reduce efficiently the overall power.	-Bandwidth is not efficiently utilised.
Network selection [19]	-Optimum network selection for multicast groups taking into consideration the users' preferences and location information.	-The optimum network selection improves the bandwidth utilisation.	-Claimed that the optimum network selection improves the bandwidth utilisation by there is no clear policy in this regard.
Scheduling and selection of radio access technology [3]	-Scheduling and selection radio access technology for the delivery of multicast content for each multicast based on network and channel conditions with time-varying.	-Efficient utilisation of bandwidth resources and supports the provision of QoS guarantees. -Maximisation of network throughput and cost service delivery.	-There is still waste bandwidth usage.

Approach	**Used techniques**	**Advantages**	**Limitations**
Network selection [60]	-It is done by selecting the network on which to deliver the content based on SNR.	-Reduce delay.	-Bandwidth is not efficiently utilised because the same content may be needed by subscribers belonging to different network and subscriber station's SNR may be good in any of the networks where the same content can be delivered through multiple networks.

2.5. Summary

The background of WiMAX and multicasting technology and its application were discussed. Multicast scheduling and network selection are the backbones of this review of related studies. In the context of multicast scheduling, a single network was considered, whereas most studies ignored QoS of multicast services, and most of them only considered the transmission rate based on the channel condition. In network selection, multiple networks were considered, and a heterogeneous network that involves cooperative networks was intensively discussed. Further, most studies focused on network selection of individual multicast group members. This implies that group members who belong to the same multicast group may receive content through multiple networks that are bandwidth consuming.

CHAPTER 3

3 VIRTUALIZATION OF WIMAX NETWORK

3.1. Introduction

Research studies [21], [64], [65] and [66] have only focused on network equipment virtualization and resource sharing. They have ignored how efficiently multicast services would perform when provisioned over virtualized networks. This chapter discusses and analyses the virtualization concept because of its relevance and benefit to users and network operators, virtualization types, and virtualization technologies. This analysis focuses on the network virtualization and application of virtualization. In addition, this thesis chapter highlights the importance of multicast service virtualization. Similarly, related studies match the objectives of the thesis which are formulated in the context of virtualization of multicast services in WiMAX networks. As seen from the previous chapter, in a heterogeneous multicast based system there is an inefficient use of bandwidth when similar multicast services are delivered through multiple virtual networks instead of being delivered through a single network. Virtualization as a solution enables the delivery of the similar multicast service through a single virtual network since virtualization allows multiple virtual networks to run on a single physical network.

3.2. Virtualization principles

Virtualization is one technique that is used to reduce the cost of information technology architectures by improving the efficiency and agility for small and medium-sized businesses. Virtualization has the ability to emulate the software functionality and hardware platforms of servers, storage devices and network resources. Thus, in a virtualization environment, functions are separated from virtual instances, and able to perform like traditional hardware. There exists a hosting hardware which supports virtual instances of functionalities. Four types of virtualization are described and summarised in references [67], [68] and [69], and these are:

- Virtualization of server
- Virtualization of desktop
- Virtualization of storage
- Virtualization of application

Virtualization of server is the act of creating virtual servers by partitioning the physical server into several small virtual servers. A hypervisor that monitors virtual machines is used to run a virtualized memory and CPU allocation of services provided over virtual instances of computing devices. Each virtual server is installed with an individual operating system, independently of the host operating system and other virtual servers.

Virtualization of desktop is the action of separating a computer desktop environment from a physical computer. Virtual desktops run on the datacenter's servers which are reliable and more powerful than traditional personal computers. The users applications have to connect and run on servers in the datacenter and this reduces the traffic and extends the network resources. It enables IT organizations to efficiently and flexibly manage the enterprise desktop environments. Two types of desktop virtualization have been defined: server-based, and client-based.

Virtualization of storage is the act of creating logical storage by aggregating all the physical storage resources that are found over the network. It creates the extension of a new hardware or software layer between the existing storage servers. There is no need for applications to determine on which particular drives, partitions, or subsystems storage the data reside.

Virtualization of application is the encapsulation of a computer program by software technology that runs on the same operating system on which it is executed. A service or application works as if it has a direct interface connecting it to the original operating system, and all resources behave as if they were managed by it, when in reality they are not. The purpose for virtualization of applications is an easy deployment and it also determines how applications can interact.

3.3. Virtualization Setup

This section discusses server virtualization environment setup since it is related to the main work of this chapter. Server virtualization hides the underling physical resources and divides them between several newly created virtual instances. For the users who use servers, it appears as if there are many physical servers, each with its own operating system, and the users are not aware of the virtualization process. There are five different techniques used in server virtualization: emulation, para-virtualization, operating system virtualization, full virtualization, and hardware-layer virtualization.

Emulation: In this type of virtualization, the hardware architecture is emulated by the virtual environment to meet the unmodified guest OS requirements. The mobile device is an example in which emulated hardware is found; mobile smart phones are emulated on a desktop PC, where application developers use the emulated environment which is shown in Figure 3.1 to test the applications designed to run on smart phones. This technique makes one computer system behave like a different computer system. The technology offers low performance and high resource utilisation [69], [70]. The following are examples of emulation: Quick Emulator (QUEMU), VMware products, Boschs and Parallels.

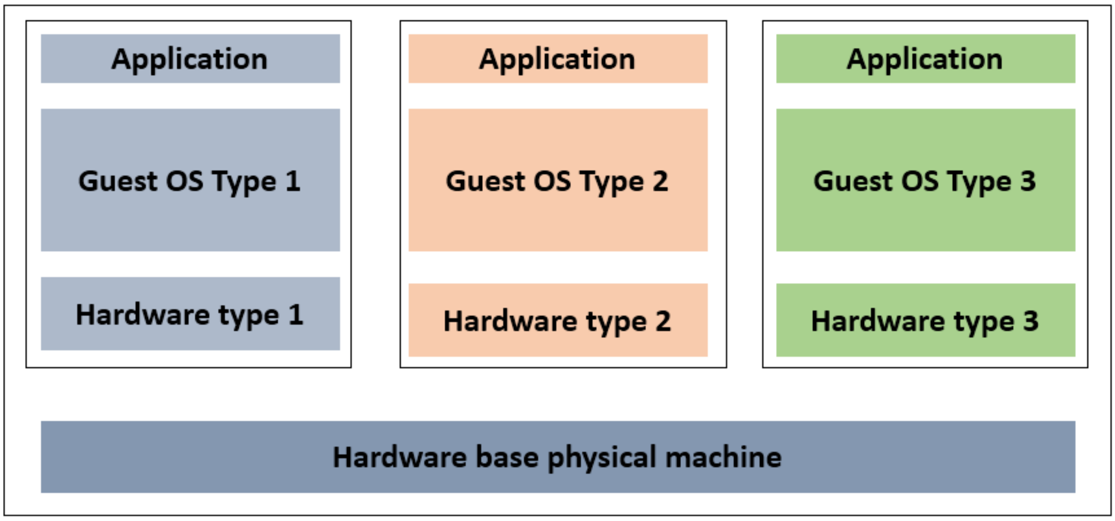


Figure 3.1. Emulated-virtualization environment.

Hardware-layer virtualization

Hardware-layer virtualization is mostly used in the server market because of its high performance in virtual machine isolation [69], [70]. VMM runs directly on hardware, as shown in Figure 3.2. It controls and synchronises the access of the guest OS to the hardware resources. In this section various existing virtualization setup and processes are described. This differs from the way virtualization is set up. In this thesis, since NS-3 is used as a tool to implement virtualization of multicast services in WiMAX networks, the emulation type is used since other simulation needs real-time implementation which requires hardware equipment for the implementation.

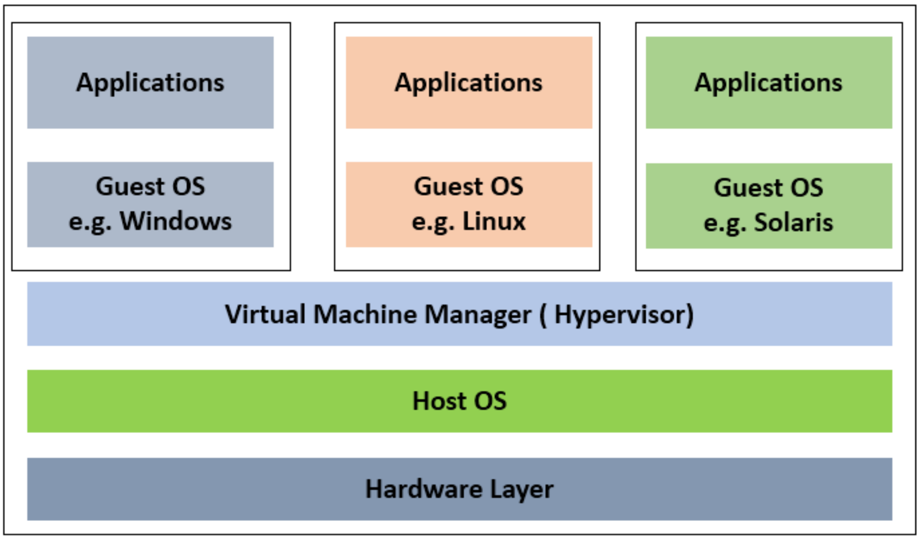


Figure 3.2. Hardware layer virtualization.

Operating system-level virtualization is the process of server virtualization on top of the operating system itself, and there is no virtual machine created [69], [70], as shown in Figure 3.3. The virtualization functionalities are completely configured within a single OS. The guest servers are isolated from one another and must use the same OS. Kernel is an example of operating system-level virtualization.

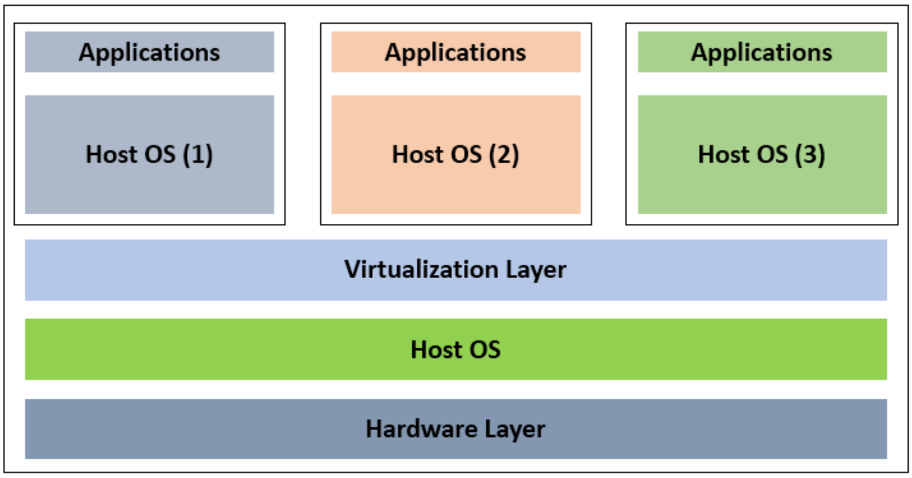


Figure 3.3. OS level virtualization environment.

Para-virtualization is a technique that modifies the guest OS and enables multiple modified OS to run on top of a thin layer called hypervisor or virtual machine monitor (VMM) as shown in Figure 3.4 below. The virtual machines run as modified OS and are aware that they are running in a virtualized environment [69], [70]. Xen, Unified Modeling Language (UML), Kernel-based Virtual Machine (KVM), Linux Containers (LXCs) and Open Virtuozzo (OpenVZ) are examples of para-virtualization.

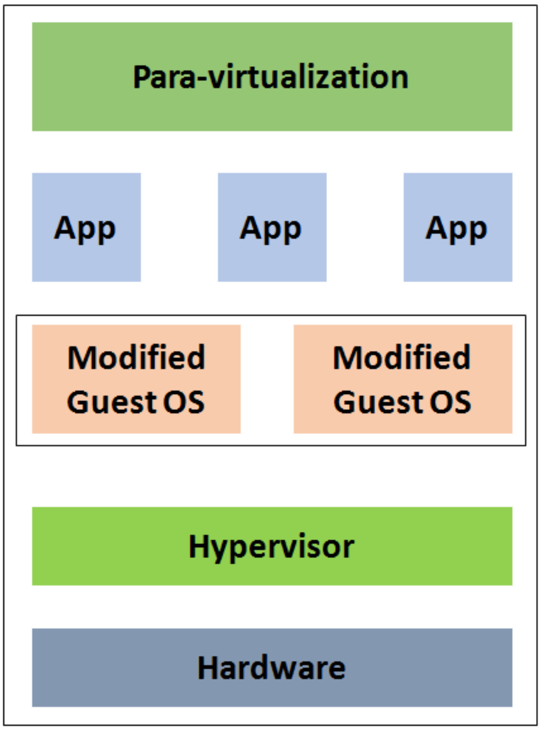


Figure 3.4. Para-virtualization environment.

Full virtualization is similar to para-virtualization. However, the virtual machine manager is required to link the guest operating system and the host hardware [69], [70]. The unmodified guest OS runs within a virtualized environment with the support of underlying hardware as illustrated in Figure 3.5 below. The hypervisor creates several virtual machines, and each runs a different OS to avoid the failure of one from affecting the other. Individual machines must be simulated and completely isolated from one another. Complete OS installations are the virtualized images which can be very big folders, and therefore significant performance hits can occur and affect input/output. VMware, Virtual Box and Z/VM (Heavy weight) are examples of full virtualization.

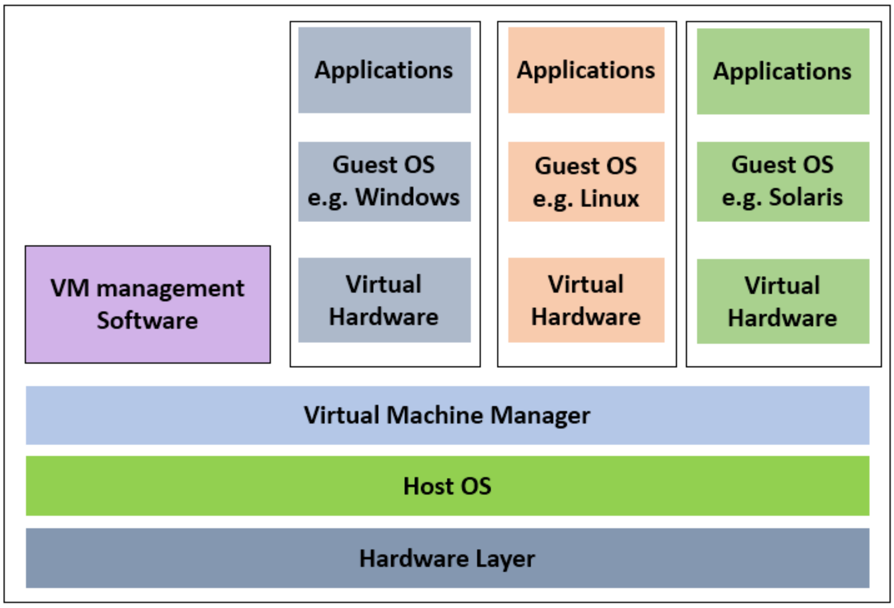


Figure 3.5. Full virtualization environment.

3.4. Virtualization Benefits

Virtualization enables the interconnection of many switches to create a single, logical entity which is controlled in a single framework. Virtualization is useful in the realisation of economic benefits. Detailed benefits of virtualization are explained as follows [68]:

a) Server virtualization decreases the number of physical servers needed and optimises the utilisation of their resources. It also reduces the maintenance of hardware costs and time the system administrator takes to perform many other routine tasks.

b) Desktop virtualization makes enterprise desktop environments flexible and manageable.

c) Application virtualization enables deployment and facilitates the interaction of applications with each other.

d) Network virtualization provides network infrastructure with high flexibility, scalability and security.

Obviously, network virtualization offers benefits like improved network scalability, performance and security. It also supports privacy and traffic segmentation, enhances end user experience, and eases the deployment of new applications and services on a network in a short time. Virtualization enables more than one operating system to run on the same server hardware simultaneously while maintaining the isolation of each virtual machine. Thus, virtualization reduces the power and the coding requirements, and there is no need for additional data centers. This reduces the overall maintenance and managing costs [68].

Virtualization makes applications much more available, agile, scalable, cheap and manageable than they were on physical servers. Virtual machines can be continuously moved from one physical machine to another. It equally solves resource limitation problems without affecting the application uptime. This is why virtualization can run cloud computing, and cloud computing is built on data centers that create the concept of a virtual data center. The data centers provide resources as an on-demand service. Virtualization enables companies to provide new applications and accelerates their deployment without losing scalability, resilience and availability. The entire data center can be restored in short time, compared to the traditional systems [67]. This thesis argues for the capability of virtualization in managing and scaling the applications, to achieve delivery of multicast traffic through a single virtual network. The following features are considered important for the benefit of virtualization [69], [71]:

Flexibility: Having the possibility to migrate a virtualized instance to another physical machine, the virtual instances can be from the host operating system with all the characteristics that any physical machine can have such as booting, resuming, pausing, and shutdown processes [69]. It also facilitates the changed virtual computer specifications while the machine is running.

Availability: During a hardware upgrade or maintenance, the virtual instances may temporarily be migrated to another computer and then migrated back to the primary computer, according to reference [69].

Scalability: As required by a system or enterprise, any device can be added or removed. This grows with the extension of the company.

Hardware utilisation: This increases as the operating system, hosted simultaneously, increases. Unutilised hardware resources can be utilised by a virtual machine during idle time.

Security: Multiple virtual machines can have issues if the resources are compromised.

Cost: By grouping smaller servers into the more powerful server, the cost can be reduced. The cost is reduced from hardware and operations because of the need for a smaller number of software licenses, personnel and floor space.

Adaptability to workload variations: A high load from one virtual machine can be solved by moving some of the resources and priority allocations to virtual machines.

Load balancing: Virtualization helps to easily migrate virtual machines to other platforms with the objective of improving performance by having optimum load balance.

Legacy applications: It is possible to continue to run a legacy application on the old OS, as a guest OS within a virtual machine, after migrating to another operating system. Hence there is a reduction in migration costs.

There are two main benefits to be gained from any virtualization technology: resource sharing and isolation [69]. Physical resources in a virtualized environment are shared among virtual machines. The physical resources comprise memory or storage, disks and network devices of the physical machine.

3.5. Network Virtualization

Network virtualization is the technique used to abstract physical network and its elements, such as switches, ports, and routers; hence virtualization is the abstraction of physical networks. Reference [72] argues that virtualization enables multiple virtual networks to run simultaneously over a shared physical infrastructure. In a virtualized environment, the network should be managed efficiently. In reference [1], network virtualization is defined as network resource allocation. For this reason, network virtualization enables isolation of physical network resources and accommodates multiple independent and programmable logical networks. Moreover, a benefit of network virtualization is that multiple physical networks may be grouped into one virtual network. Alternatively, one physical network can be divided into multiple virtual networks; each being operated by separate network operators as stated in reference [1], [69], [70]. Network virtualization results in flexible and automatic network configuration which leads to faster and more reliable deployment with reduction of manual intervention. Network virtualization also allows the network to extend beyond the expected locations in public cloud [73]. Since network virtualization enables multiple network operators to run on a single physical network and facilitates them to share network resource among their users, this gives flexibility to implement the virtualization of multicast services and allows the delivery of similar multicast traffic through a single virtual network with the programmability support of network virtualization.

Further, the difference between server virtualization, computer virtualization, and network virtualization is that in network virtualization, network components such as routers, switches, and links are virtualized. Thus, the concept of virtualization of these network components operate the same way as server and computer virtualization operate [1]. Network virtualization differentiates the aspect of the conventional Internet Service Providers (ISPs) by dividing it into two different bodies, such as Infrastructure Providers (InPs) responsible for managing the physical infrastructure, and Service Providers (SPs) which are in charge of creating Virtual Networks (VNs) [70]. Thus, they can gather resources from several InPs and provide end-to-end service.

Originally, network virtualization started in wired network; recently it has been extended to wireless network. Thus, network virtualization is a method used for efficient and flexible achievement of future mobile networks, where multiple access network standards compete and coexist. For example, in heterogeneous networks, the interoperability and the resource allocation among different technologies are some of the potential issues to solve [17] because of coexistence and convergence of wireless technologies in a service-oriented infrastructure. This is why mobile network operators' investments and network performance improvements are scaled down by the use of network virtualization. To this end, this thesis has sought to analyse the network virtualization environment which enables shareability of physical infrastructure and resources among the multiple virtual networks. Hence, network virtualization reduces costs and saves energy.

Specifically, the server virtualization has been extensively applied in cloud computing. With server virtualization, the services may be provided on demand, and the management of computing resources can be managed flexibly [1]. Convincingly, in the server virtualization processes, the interface should also be virtualized, as shown in Figure 3.6 because interface virtualization facilitates access to multiple operating systems. However, this does not include the virtualization of the routers and switches that are part of the network.

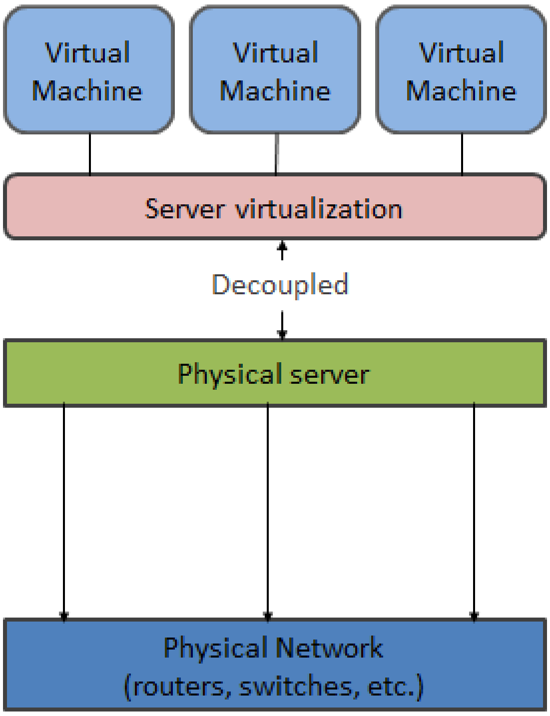


Figure 3.6. Server virtualization [1].

The process of decoupling the infrastructure from its functionalities is an existing network function virtualization [1], as described in Figure 3.7. In server virtualization, a single server is shared among multiple users through virtual machines (VM). This is done by abstracting and separating the hardware from its functionalities. The network infrastructure is separated from the services it provides. Network components such as routers, switches, and firewalls modules are also decoupled from network virtualization.

Nevertheless, deployment of these virtual networks may be dynamically allocated on demand. Therefore, a benefit of network virtualization is its ability to enable a more flexible management of the interconnection between physical servers in large data center [1]. It was seen from the previous sections that network virtualization enables sharing of network resources between multiple network operators. This section described the elements of networks which can be virtualized, including routers and switches, to enable the sharing of the network resource. In this thesis, the elements which are virtualized are routers, links, and base stations for the implementation of multicast service virtualization framework which enables the efficient use of bandwidth and improves the network performance.

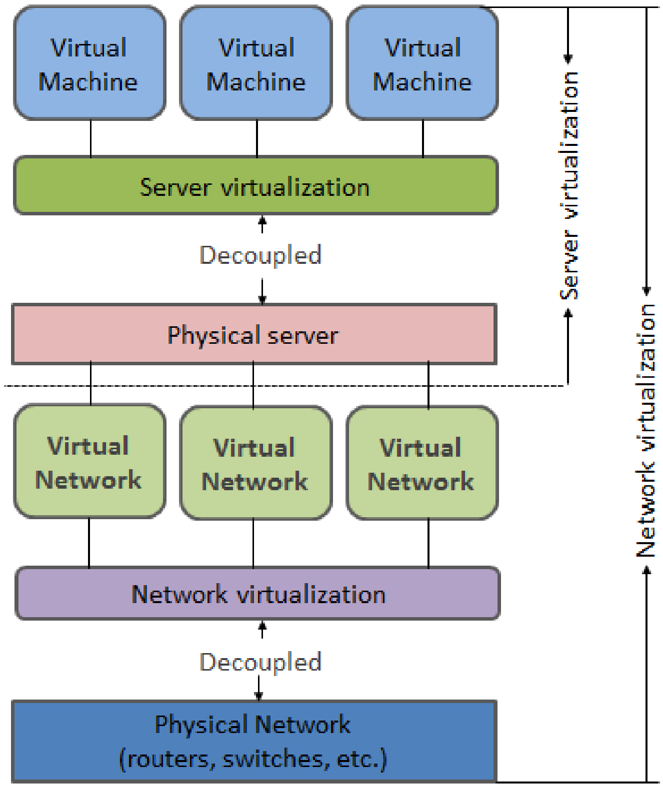


Figure 3.7. Network virtualization.

Based on different concepts and technologies, there are various types of network virtualization, such as a Virtual Private Network (VPN), Virtual Local Area Network (VLAN), multi-user access techniques, and Software Defined Network (SDN) [1]. From all the definitions stated above, network virtualization can be summarised as “network resource sharing” because virtualization is a combination of the following aspects: abstraction of resource; partition of resource; aggregation of resource; control centralization; and data plane and control plane separation. Network virtualization techniques can be classified on the basis of network components where the virtualization is deployed. Network virtualization is divided into two main parts according to their applications: industry oriented and research-oriented virtualization as stated in [74], [75]. In industry, virtualization can be done at three levels: device virtualization, link virtualization and network virtualization. Thus, device virtualization is performed at NIC and router level; link virtualization is performed at the physical channel multiplexing and channel bandwidth; and flow or packet. Similarly, virtual networks can be overlay networks, virtual private networks and virtual sharing network. Further, research application of virtualization comprises Next-Generation Network (NGN) test beds and protocols virtualization. Thus, Table 3.1 shows a detailed explanation of all the descendent virtualization levels.

Table 3.1. Different aspects of network virtualization [74], [75].

<table>
<tr><td rowspan="13">Network virtualization Industry-oriented</td><td rowspan="5">Device virtualization</td><td rowspan="2">NIC virtualization</td><td>Software-enabled NIC virtualization (vNIC, vSwitch)</td></tr>
<tr><td>Hardware-assisted NIC virtualization (SR-IOV)</td></tr>
<tr><td rowspan="3">Router virtualization</td><td>Router in virtual OS (vRouter)</td></tr>
<tr><td>Router control virtualization (VRF)</td></tr>
<tr><td>Hardware-partitioned router</td></tr>
<tr><td rowspan="5">Link virtualization</td><td colspan="2">Physical channel multiplexing (TDM, FDM, CDMA)</td></tr>
<tr><td rowspan="2">Bandwidth virtualization (channel bandwidth)</td><td>Circuit Switching</td></tr>
<tr><td>Reverse multiplexing (optical)</td></tr>
<tr><td rowspan="2">Data path virtualization (packet, flow)</td><td>Labels (ID VLAN, MPLS)</td></tr>
<tr><td>Tunnels and encapsulation (GRE)</td></tr>
<tr><td rowspan="3">Virtual network</td><td colspan="2">Overlay network</td></tr>
<tr><td colspan="2">Virtual private networks</td></tr>
<tr><td colspan="2">Virtual sharing networks</td></tr>
<tr><td rowspan="10">Network virtualization research-oriented</td><td rowspan="7">NGN Testbeds</td><td colspan="2">Planet lab</td></tr>
<tr><td colspan="2">VINI& Trellis</td></tr>
<tr><td colspan="2">GENI</td></tr>
<tr><td colspan="2">VIOLIN</td></tr>
<tr><td colspan="2">Emulab</td></tr>
<tr><td colspan="2">G-lab & onelab</td></tr>
<tr><td colspan="2">SAVI</td></tr>
<tr><td rowspan="3">Virtualization protocols</td><td colspan="2">X-Bone</td></tr>
<tr><td colspan="2">UCLPv2</td></tr>
<tr><td colspan="2">OpenFlow(Datapath virtualization)</td></tr>
</table>

3.5.1. Network Virtualization Techniques

In the past years network virtualization has gained important focus. Network virtualization enables end users to be simultaneously connected to more than one virtual mobile network operator. This is why global naming and addressing is required to identify physical and virtual elements. The literature reviewed has revealed issues that surfaced prior to the creation of virtual networks, and these should be taken into consideration. Resource virtualization such as server virtualization, node virtualization, and router virtualization build up virtual networks. However as stated earlier in this thesis, resource virtualization such as link virtualization, router virtualization and node virtualization (i.e. base stations) were built up to achieve the objective.

The literature on network virtualization focuses on resource management between virtual networks. However, most works ignored the flow allocation problem. The solution to the flow allocation enables similar multicast content to be delivered through a single virtual network, instead of being delivered through multiple virtual networks. This thesis has demonstrated how the selection of virtual networks operates and how multicast traffics are allocated to virtual networks to improve the network performance and apply bandwidth efficiently. The following paragraph explains resource management techniques used in network virtualization.

Research in [21] surveyed the fundamental steps of resource discovery and resource allocation which are required in network virtualization process. In the virtualization process, virtual networks are isolated from each other by decoupling the network infrastructure from the services they provide to avoid failure in a virtual network that may be caused by another virtual network. The study also described challenges of the process of embedding wireless virtual network to wireless physical network. The survey focused on resource allocation by showing that heuristic approaches are the most commonly used techniques.

A heuristic approach produces a solution for solving the problem at hand in a reasonable time frame. This solution may not be the best one, or it may simply approximate the exact solution. However, it is still valuable because finding it does not require prohibitive time. Still, the study ignored the cooperation among multiple network operators in a virtualized environment. MILP is rarely used as a resource allocation for the biggest problems. It was used in this thesis since the problem formulation is not large, and this resolves the problem of flow allocation, which is the focus of this research work.

An algorithm for a virtual network embedding in a multi-hop wireless network was proposed, based on link interference challenges [22]. A request from the virtual network that requires an amount of bandwidth and CPU was considered to maximise the substrate network revenue but the cooperation of virtual network was ignored. The concern of this thesis is to integrate heterogeneous network and multicast services for the delivery of similar multicast content, through a single virtual network.

Reference [23] established a virtual network framework based on QoS classes which ensure QoS requirement for each traffic and cost reduction for the company. The client's traffic is forwarded to the appropriate virtual network, depending on the traffic class. Thus, the framework differentiates traffic according to defined QoS classes. The framework's idea is based on the particular needs of each client and corresponds to the cost of each network configuration for its effectiveness achievement. However, the traffic allocation considered was within the same network where the creation of virtual networks is based on QoS, and there is no cooperation of networks considered in that system. In [24], an end-to-end technique for managing virtual network resource with a two-dimensional architecture from service providers and network providers' points of view was presented. Both architectures provide virtual network resource management in horizontal and vertical dimensions. In vertical case, resources are managed across network operators through router and network link virtualization, while in horizontal case, resources are shared across service providers. However, the research did not show how resources can be managed in such an environment.

In [76], link and node virtualization was done, and a machine learning-based approach to manage virtual network resources dynamically was proposed. Decentralisation of network substrate and development of a learning algorithm was introduced in each node and link substrates to enable self-organization of the network. While most of the work allocated resources statically, the learning algorithm proposed was to allocate resources dynamically through feedback information of resource utilisation from virtual networks, and re-allocate the unused resources to other virtual networks. The resource allocation algorithm ensures that virtual network packet drop rate and virtual link delay are not affected. Nevertheless, the research did not consider the provision of multicast services over virtual network, or cooperation between mobile network operators in a virtualized environment. Consequently, the bandwidth is not efficiently used since they did not exploit the benefit of integrating multicast services and network virtualization.

Research work in [77] performed switch level virtualization to enable sharing of the forwarding plane of the hardware with numerous logical networks, by ensuring isolation and hardware forwarding speed using FlowVisor. This allows a multiple network experiment to run in parallel with the generation of traffic and it provides isolation with hardware forwarding speeds supported on the same platform. The work allocates the bandwidth to flow in each slice, and no cooperation of multiple virtual networks was done. Multimedia services demand high bandwidth and, as the number of users requiring these services steadily increase, the bandwidth management in wireless networks becomes more complicated. The integration of virtualization and heterogeneous networks in a multicast based system is a solution to these bandwidth problems; however this was not solved by the work of the literature.

In [78], iMark identity framework was proposed. This enables each virtual network in a virtualized network environment to implement its own addressing, routing, transporting and naming mechanisms. Thus, a heterogeneous identifier was considered to ensure end-to-end delay connectivity. The iMark enables end hosts to communicate with each other inside and outside their networks through a set of controllers, adapters, and well-placed mappings, without sacrificing the autonomy of the concerned virtual networks. However, the study did not show how to allocate resources and thereby provide a solution to the problem of bandwidth limitation in wireless networks.

Vendors should encourage flow level virtualization to add an OpenFlow program which manages and directs traffic among switches and routers from various vendors as stated in [79]. The proposed OpenFlow supports experimental tests on campus, to avoid public exposure of internal workings of vendors' products. OpenFlow is an Ethernet switch with a built in flow-table and has a standardised interface that enables the addition and removal of flow entries. However, the work did not consider network resource management which is a crucial issue in network virtualization environment. This thesis built on an idea from the literature about flow level virtualization, and came up with the idea of integrating heterogeneous networks by sharing resources in a virtualized environment and designing the model which is used for the flow allocation problem, to use bandwidth efficiently and improve network performance.

An efficient online virtual network request algorithm was proposed in [80]. This algorithm is a combination of a scheduling algorithm and a Karnaugh map-embedding algorithm that embeds virtual network requests. The embedding decision was based on the time window, buffer, queuing and re-embedding mechanism. This achieves a more efficient performance than a conventional packing problem algorithm. Research in [80] chooses virtual network to be dynamically accommodated according to the resources available upon their request. It differs from this thesis because the virtual networks remain the same and the flows are allocated to various virtual networks, since only a flow is allocated to a single virtual network for the efficient use of bandwidth.

Research in [81] implemented a traffic classifier and scheduler using priority queuing and deficit round-robin. It classifies the packets based on their virtual local networks identification and puts them in the appropriate queue applying a programmable platform for processing packets, based on hardware capability. Thus, the priority queuing scheme offers a relative priority to a given slice, and the deficit round-robin scheme allocates weighted-fair quantum sizes, based on required bandwidth flows. This provides QoS to virtualized network slices. However, the main contribution of this research, which is to allocate the flows to virtual networks for the efficient use of bandwidth by enabling the virtual networks to share the resources in a multicast based system, was not shown.

Research in [82] developed a well-defined virtual network resource management framework by considering the network topology. The intelligent virtual network resource management is based on the traffic flow, network resources, and user requirements information. The algorithm maps traffic requirements with network resources to create the virtual network. Thus, the virtual networks are created dynamically based on the physical network and incoming traffic flows. Obviously, this leads to an improved virtual network capacity. However, it does not show how bandwidth is efficiently used and, similarly, it does not discuss multicast flows. This thesis overcomes the bandwidth limitation problem by considering a multicast service-based system in a virtualization environment.

A game theory model was applied to enable efficient interaction between service providers (SPs) and infrastructure providers (InPs) [83]. The model enables the allocation of bandwidth to virtual networks that use the Nash Equilibrium concept. Noticeably, virtual networks are assigned traffic before allocation of traffic which leads to inefficient bandwidth utilisation, while in this thesis, virtual networks are selected dynamically to be assigned the multicast flows to efficiently use the bandwidth and improve network performance, and this is not the focus of the literature.

Further, virtualization may work in business where relevant business orientation has been conducted, as described in [84]. Investigation on the current technological, regulatory, and business landscape from the network infrastructure perspective has been done. Practically, different methods and technical network sharing solutions were proposed. This study introduced a savings estimation model on capital and operating expenditures. Similarly, it assessed the benefits of "Managed Services" for the case of shared networks. It is a potentially effective and attractive model that overcomes some of the challenges caused by sharing the same infrastructure. However, the work did not consider the efficient utilisation of bandwidth or how the network resources would be shared among multiple virtual networks. It also did not consider how multicast services could be provided over virtualized networks.

Recently, research was extended from wired network virtualization to wireless networks virtualization such as WiFi, LTE, and WiMAX networks virtualization. References [11], [85] surveyed various architectures of wireless network virtualization and the technologies that are enabled by wireless network virtualization. Similarly, the current wireless virtual resources and wireless virtualization were classified into three categories: spectrum virtualization, flow virtualization, and network virtualization. However, virtual network selection and multicast services over virtualized WiMAX networks were not the survey focus. Instead a wireless network and virtualization device were mostly employed. This includes base station and access network virtualization. As a result, the concept of virtualization was the same as in server virtualization. However, this thesis integrates network virtualization, heterogeneous networks and multicast based system for better network performance.

The research in reference [86] introduced the LTE virtualization where the spectrum was shared between virtual network operators that used multiplexing gain based on their business policies. Although the focus of the study was spectrum sharing, virtual network selection, multicast service based system, and allocation of traffic to virtual networks to improve the bandwidth utilisation efficiency was omitted. However, this thesis focused on virtualization of WiMAX network by considering multiple WiMAX networks as heterogeneous networks and performed traffic allocation to improve the network performance and the efficient use of bandwidth.

The study in [87] performed flow level virtualization by fostering the innovation and differentiation of network operators and facilitating the customization of base station. This enables the running of customised schedulers within slices. The technique in question offers effective virtualization of wireless resources in WiMAX networks and enables cellular network to provide quality experience to users. Researchers designed and implemented a virtualized WiMAX framework. The framework enabled flow virtualization by slicing the resources of different virtual network operators. This work has considered only two slices, each slice with only one subscriber station. Unfortunately, the interface of multiple base stations was not investigated because only one base station was considered in the study. However, the co-operation of virtual networks was not considered since the work did not deal with multicast traffic. This can be delivered over a single channel and virtual network. The research has also surveyed wireless network resources that can be virtualized such as:

- Bandwidth frequency channels
- Time slots
- Air interface
- Radio resources

It is worth recalling that wireless resources shared among multiple virtual networks involve the above resources. These shared resources were addressed in the virtualization of wireless network where virtualized components are passive components that consist of antennae, tower, sites, feeder and power supply, and active components like radio network, radio base station, and transport links. Since the objective of this thesis is to enable the interchange of multicast services in virtualized multicast services, the virtualization in this work was investigated on the basis of service. This is why multicast traffic had to be allocated to virtual networks by selecting the best suited virtual networks to optimise the network performance and use the bandwidth efficiently. Resource sharing and management in network virtualization have been done before, and the main contribution of this research is to virtualize multicast services of heterogeneous networks composed of WiMAX networks, by allocating traffic to the virtual network for improved network performance.

Reference [88] developed a weighted fair algorithm for sharing resources based on airtime fairness. A virtualized architecture for layer 2 of mobile WiMAX networks frame switching was developed. Management mechanisms were established to enable the isolation between those slices required to support repeatability. The research proposed a virtual base station to solve handover problems in WiMAX networks, and developed a cognitive virtualization platform to facilitate the end to end slicing on wireless and wired networks. This platform accommodates network virtualization technology and cognitive radio technology on the same infrastructure which leads to dynamic reconfiguration of the network resources. However there is no heterogeneity of networks, and it is not a multicast-based system, which is the focus of this thesis.

Research work in [9] did virtualization of radio medium through multiple network operators to share the same LTE physical resources. The sharing of spectrum was worked out based on two algorithms such as static and dynamic allocation. In static allocation, the spectrum is allocated beforehand and remains stable while in dynamic allocation; the spectrum changes based on the traffic overload. On the other hand, this thesis emphasises that multicast traffic is dynamically allocated to selected virtual networks. Thus, the end user may receive content from a virtual network other than the home network because isolation was not taken into consideration, as is the case with this thesis where virtualization of multicast service enables multiple network operators to run on the same physical infrastructure.

The algorithm designed in [89] allocates sub-carriers and power transmission resources to virtual networks. The work first created virtual networks and allocated the network resources to the created networks. The resource allocation is done by considering traffic load and current information of the channel. The aim of the paper was to achieve efficient utilisation of network resources and isolation between virtual networks. However, since the study does not specify how multicast traffic shares the resources of the network in the virtual networks, this thesis is a solution to the problem of bandwidth utilisation by selecting the best virtual network through which to deliver common content to the subscribers, for better network performance and efficient use of bandwidth.

Reference [64] performed frequency virtualization to enable multiple interfaces on a node so that it can run multiple experiments simultaneously on different frequencies. Frequency division duplex access technique was achieved by enabling each node to run two concurrent user level operating systems. The latter provided access to a radio card. To reach this, user mode Linux was applied to the virtualization process. The work focused on node virtualization; however resource allocation policy between virtual networks was ignored. This idea was brought to this thesis as a way to accommodate multiple virtual networks on a single physical network. However the network virtualization, multicast services and heterogeneous networks were integrated to facilitate the delivery of similar multicast content over a single virtual network. This has not been done anywhere else in the literature according to my knowledge.

Multiple virtual cellular network operators should be able to own and run the networks in a fully competitive manner. A cloud computing paradigm-influenced concept was proposed and presented in [90]. This cloud cellular network enables cellular networking utility. In a feasibility study of the proposed model, an operators tried a newly developed auction method. The method facilitates the auction of a spectrum of endless and ongoing items, different to a set of discrete and separate items. This offers the opportunity to the cellular network entities of retaining a far more complex control on the network.

In [4], a network resource allocation algorithm was developed based on a contract approach. The allocation of network resources is managed by the hypervisor which allocates the spectrum based on a contract of each virtual operator. For this reason, four contracts were considered for four virtualized operators: fixed guaranteed, dynamic guaranteed, best effort with minimum guarantees, and best effort with no guarantees. Further to this, applications provided to respective virtual networks were: video streaming, VoIP, VoIP with best effort, video on demand and small VoIP. The results showed that even small operators can be accommodated in a virtualized network, and that a virtualized network can operate efficiently. Although their focus was to share the bandwidth between operators, they did not efficiently manage to achieve their focus. Thus, with the use of multicasting there is a further improvement on efficient utilisation of bandwidth. It was the objective of this thesis to achieve the delivery of similar multicast content through a single virtual network for the efficient use of bandwidth and better network performance.

References [12], [13], a flow level virtualization framework in cellular networks, was designed and implemented. In the implemented substrate, the resources were provided based on bandwidth and time slots. The research activities enabled customised resources to be provided within a base station based on slices. Thus, a network virtualization substrate was designed and network resources were isolated from users, but service providers were not isolated. Thus the network resources were shared according to the policies or arrangements set by different virtual network operators. Flow level virtualization was considered, based on mathematical modelling, to achieve bandwidth-based and resource-based provisioning. The resources were allocated to the virtual networks based on their requests. However multicast services were not their concern. This thesis integrates network virtualization with multicast services and heterogeneous networks to use the bandwidth efficiently and improve network performance.

The research in references [65], [66] proposed virtualization of radio access network architecture by spectrum virtualization. The architecture achieves vertical virtualization, programmability, and horizontal convergence of the heterogeneous network. The study demonstrated a good example of feasible radio access network virtualization methods based on the use of the same spectrum between different radio access networks. However, the work did not deal with the selection of the radio access network and multicast services for the efficient utilisation of the bandwidth. Only virtualization and heterogeneous networks were integrated. However, there is no integration of multicast services. Thus, the bandwidth is not efficiently used for multimedia services which require high bandwidth traffic. Hence this thesis considered multicast services over virtualization and heterogeneous networks to improve the efficiency use of bandwidth and improve the network performance.

Research activities in [91] performed virtualization of wireless networks with the focus on the problems caused by randomness. To solve the randomness problem, an algorithm was designed to allow multiple virtual networks to operate in a distributed fashion. The designed algorithm is a solution that maximizes the aggregate throughput of the network to the satisfaction of users. They also presented a new method of charging new users fairly, when users request to join the system by estimating the price which performs the system cost measurements.

Reference [15] proposed a new wireless network virtualization framework. This decouples service providers and network operators from each other. Obviously, the network operator is responsible for managing the spectrum and the service provider is responsible for the quality of service. The interaction between these two entities has been modelled as a stochastic game.

The research also developed an online learning algorithm that enables the service providers and network operators to update the functions value and conjectural prices, respectively. The proposed framework deals with the channel conditions and dynamics in traffic characteristics. Network virtualization enables heterogeneous networks to run on the same physical infrastructure, but the multicast service, which is the focus of this thesis, was not their concern.

Reference [92] studied and demonstrated the feasibility of controlling air time fairness of slices during the running of an appropriate scheduler at the base station. They designed a virtualized infrastructure that enables users to obtain at least an allocated percentage of base station resources. This was in case of the saturated and degraded link that puts a policy in place to play a dynamic rate allocation.

The research in [14] proposed a Nash equilibrium algorithm for rate allocation in virtualized wireless networks. The algorithm selects conjectural prices and announces a computed rate allocation at each time slot. This rate allocation considered point-to-point transmission where there was less efficient use of bandwidth, since service providers bid for network resources. Authors have only considered multiple services providers with a single network operator. This thesis focuses on multiple service providers and multiple network operators for the delivery of similar multicast traffic through a single virtual network to users who belong to different networks.

Research activities in [8] designed an optimised scheduler for radio resources that provides better QoS to users and optimum network performance. Apart from this, the work proposed a novel wireless network virtualization framework through spectrum sharing and multi user diversity gain that uses developed LTE radio analytical models. Though the study considered multi users diversity gain, they have ignored multicasting service which is an efficient tool for better bandwidth use. Besides, multicast content can be delivered over a single channel.

In reference [93], virtualization of user device network interface is done. A user device can have many virtual network interfaces, where each virtual network interface can be connected to the surrounding APs. A virtualized system was designed by means of virtualizing the interface. This interface is virtualized to behave like multiple network interfaces and allows it to connect to multiple access points. This setup is controlled by the network virtual machine management. This increases the number of multiple users who can be connected. However it does not solve the problem of how to use bandwidth efficiently, and multicasting was ignored.

The work reported in [94] accomplished virtualization of wireless access point equipment using Xen, where users can access different services from different virtual operators. They enabled the virtualization of physical wireless interface from an access point. Still, the solution developed has some drawbacks such as the need to know the characteristic of the flows to be treated in the access points. This also has the same problem as the previously cited work. This thesis is based on the theory that users from different networks have multiple interfaces for each access networks. But in the case of this current thesis, instead of having different access networks, multiple WiMAX access networks are considered and users do not need to have multiple interface for receiving content from any virtual network. This was not the case in the literature.

A framework for the virtualization of wireless networks is proposed in [95]. It focuses on virtualization of the air interface, where different operators share the spectrum. Scheduling algorithms based on multiplexing and multi-user diversity within a virtual network are developed. On multiplexing, the diversity spectrum is allocated depending on the traffic load. A highly loaded virtual operator is allocated more bandwidth compared to others; while for multi-user diversity, the air interface resources are allocated according to a channel condition, that is, a user with a reliable channel was allocated the spectrum. Static and dynamic implementations were done. Multicast services were not considered and the interchangeable service among network operators was not the focus of the research. Virtualization which enables resource sharing is not new; what is important is the integration of multicast services in heterogeneous networks and the allocation flows to the virtual networks for network performance improvement and efficient use of bandwidth.

3.6. Multicast Virtualization

In spite of all the major research work previously mentioned, one very important piece of the puzzle is still missing. "Multicast Services" Virtualization, according to the best of the author's knowledge, has not received the appropriate attention it is entitled to, and little work has been done in this field. According to the literature in the previous section on network virtualization, none of them mentioned multicasting in network virtualization. This section reviewed the work related to the multicast virtualization, as the focus of this thesis is virtualization of multicast services in WiMAX networks. All the research done in virtualization did not allow for the interchangeable services between network operators because their purpose was the isolation of services. However, as multicast service is the focus of this thesis, and many users may request similar content, isolation was not considered.

There exist two scenarios for multicast service virtualization as stated in reference [96]. In the first scenario, both the source and receiver are on the same virtual network. The content distribution tree is based on a specific Virtual Network (VN) and protocol independent multicast (PIM) instances. The second scenario is when the source and receiver are in different virtual networks. These enable different users to access multicast content delivered by a multicast stream in another virtual network. Figure 3.8 below shows a scenario where a multicast server with a Network Interface Card (NIC) 802.1q is set up. It also shows an end-to-end virtualization in which a complete isolation of resources, networks and users is considered. For example, if a user is subscribed to a service which has a source in its network or another one, the service provided by any other network can be received. This generates separate streams to be sent to different Virtual Local Area Networks (VLANs).

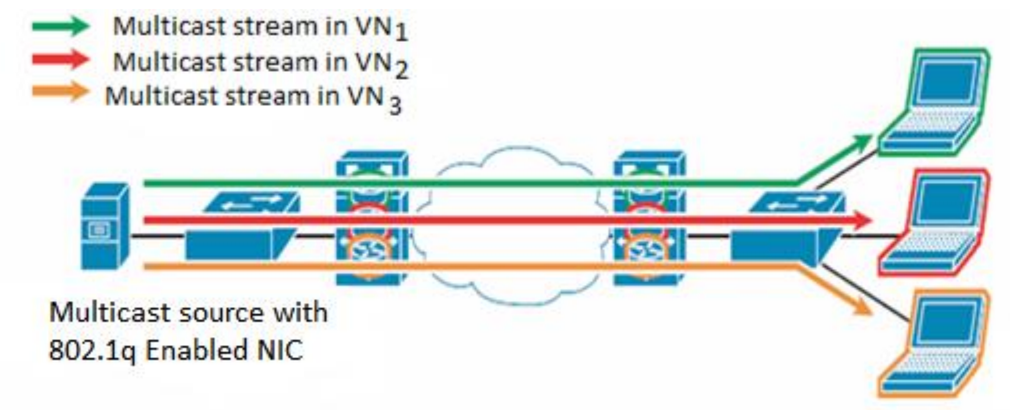


Figure 3.8. Multi-NIC multicast source environment [96].

Figure 3.9 below illustrates a source shared by multiple virtual networks, where a central policy enforcement point (Service Edge) is used to allow the communication between the source and the client by the replication of multicast content.

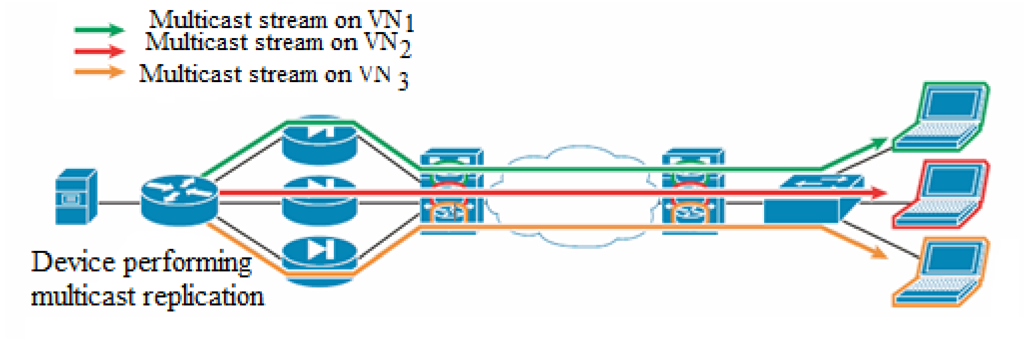


Figure 3.9. Replicated multicast source environment [96].

Since the bandwidth resource is rare in the field of networking, the work in reference [97] proposed a virtualization framework for resource provision that enables services which require high bandwidth to coexist on a single infrastructure. To solve the problem of bandwidth, they developed an algorithm that reduces the number of servers to satisfy all requests of those services. However the study ignored bandwidth efficiency use and advantages of multicast services. This is why, with the use of virtualization and advantages of multicasting service on top of the theory of heterogeneous networks, multicast traffic can be delivered through a single virtual network - thereby providing a solution to the bandwidth management problem.

The work in reference [98] investigated the problem of mapping network resources in the perspective of virtual multicast service-oriented network with the concern of delay and delay variation constraints. The work also proposed connectivity architecture for better network services for a cost effective method that supports the delivery of IPTV over wide area IP multicast that runs over a reliable virtual network. The connectivity layer was introduced between service layer and infrastructure layer which uses virtual link purchased from the infrastructure provider. The objective of connectivity architecture for better network service is to improve coverage, reliability and network performance. Investigation of mapping multicast service in virtual networks was done, taking into consideration the delay and delay variation [25]. The results have achieved minimum load balancing from service requests and thus increased the feasibility ratio of virtual multicast network requests. However their study did not focus on how to deliver the content to users [25]. This thesis considers the number of flows and virtual networks to allocate flows to a virtual network. However the mapping of multicast services does not show how to efficiently use the bandwidth in a virtualized environment, which is the focus of this thesis. Table 3.2 summarises briefly the above stated network virtualization techniques.

Table 3.2. Comparison of network virtualization techniques

Approaches	**Proposed techniques**	**Advantages**	**Limitations**
Resource discovery and allocation in network virtualization with mainly heuristic solutions and rarely MILP [21]	-Heuristic, MILP, Graph theory approaches for resource discovery and allocation.	-However, since the problem is NP hard, heuristics and meta-heuristics are and will remain useful for very large instances of the problem.	-Cooperation of multiple network operators in virtual environment was not considered. This takes much time for resolution.
An algorithm for virtual network embedding in multi-hop wireless network [22]	-Graph theory. Heuristic solution.	-To optimise the revenue of the provider.	-A single virtual network was considered hence cooperation of virtual network does not exist.
Traffic classification based on QoS and allocation to virtual networks [23]	-Machine learning techniques such as Naïve Bayes and Decision Tree for traffic classification and allocation.	-Effective classification process and traffic allocation.	-No involvement of heterogeneity of the networks.
Virtual network resource management [24]	-Enables SPs to bind VNRs rented from heterogeneous NPs and facilitates NPs to perform cost-efficient allocation of VNRs.	-Accelerate the realisation of virtual resource sharing in the future Internet business marketplaces.	-Uncertainty of virtual resource availability and lack of stringent network robustness for real-time applications. No clear policy of resource management. No efficient use of bandwidth.

Approaches	**Proposed techniques**	**Advantages**	**Limitations**
Switch virtualization that enables multiple network experiment to run on the same infrastructure [77]	-A set of flows forms a slice which is assigned minimum data rate by a FlowVisor.	-Enable hardware forwarding plane to be shared among multiple logical networks, each with distinct forwarding logic.	-No policy was put in place on how to assign the bandwidth to slices.
Online karnaugh -map embedding algorithm [80]	-An online algorithm was used to schedule Virtual Networks (VNs) requests using karnaugh-map to embed the Virtual network requests based on time window, buffer, and queuing.	-Efficient performance.	-No cooperation between mobile network operators.
Virtual network control using intelligent management and cognitive methods [82]	-Dynamic creation of virtual networks based on the traffic flows, requirements of resources and the physical network.	-Offers improved virtual network capacity	-However, it does not show how bandwidth is efficiently used and does not discuss multicast flows
Game theory and Nash Equilibrium. The concept was used to manage resources [83], [14], [15]	-Using game theory to enable interaction between InPs and SPs. Using Nash Equilibrium to allocate bandwidth between virtual networks.	-Efficiency bandwidth allocation.	-Static allocation of traffic to virtual networks, while in this thesis virtual networks are selected dynamically.
Spectrum sharing between virtual network operators using LTE [86]	-Multiplexing gain based on network operators business policies like the current traffic load of the virtual network and the statistical characteristics of real-time traffic.	-Observe the statistical characteristics of real-time traffic for the accurate spectrum estimation required to each virtual operator.	-The virtual network selection and allocation of traffic to virtual networks which improves the bandwidth use efficiency was not considered.

Approaches	Proposed techniques	Advantages	Limitations
A contract based hypervisor algorithm estimates needed bandwidth of virtual operator [4]	-The information about user channel conditions, loads, priorities, QoS requirements, contract policy of each of the virtual operators is used to schedule the air interface resources between virtual operators.	-Enhancement of the overall resource use. Possibility of opening the market to small operators.	-No allocation of traffic to virtual networks, no QoS guarantee policy was provided.
Mapping multicast services to virtual network [25]	-Mapping of multicast services was done based on delay and delay variation.	-It offers minimum load balance.	-Bandwidth is not efficiently utilised.

3.7. Summary

This chapter reviewed the related literature and studies the concept of virtualization in previous research. Most related studies analysed virtualization where network resources were shared, but did not show how the resources were shared among the virtual networks. The network selection of virtual network for efficient bandwidth use was ignored in the literature. In addition, the chapter discusses works on virtualization of multicast services. Very few scholars proposed how multicast service virtualization can be implemented, and the cooperation among network operators was ignored.

CHAPTER 4

4 WIMAX MULTICASTING VIRTUALIZATION

4.1. Introduction

The previous chapters discussed the background and related works guided by the research objectives of this thesis. However, the aim of this chapter is to design a virtualized multicast service framework that enables efficient use of network resources that support interchange of service delivery. This is worked out between multiple networks on a shareable network infrastructure and the development of an algorithm that efficiently allocates multicast traffic to virtual networks. In this chapter, an optimum multicast rate and scheduling of multicast traffic is also designed. The Generalized Assignment Problem in [99] is applied in order to model the allocation of multicast traffic to virtual networks because the GAP allocates exactly one flow to only one virtual network to maximise the total throughput of the assigned flow. This is done without assigning multicast flows to any virtual network which exceed the total bandwidth greater than the virtual networks capacity. Thus, MILP [62] is used by allocating a flow to a single virtual network to solve the flow allocation problems. MILP assigns binary digit 1 whenever a flow is allocated to the virtual network and otherwise digit 0.

The chapter starts with the model of virtualization for multicast services by using GAP and analyses how the GAP problem was mapped to linear programing problem. After this, the optimal solution of multicast flows allocation to virtual networks is described. Finally, the multicast scheduling is presented.

4.2. Definition of Multicast Service Virtualization

This chapter engages the reader with the key concepts of this thesis. It is relevant to the analysis of related works in Chapter 3. The following are the key concepts: heterogeneous networks, network virtualization and multicasting where scheduling and rate selection of multicast traffic are explained. In heterogeneous networks, there is no efficient use of bandwidth when delivering multicast content. This is because when there are multiple users who belong to different networks, their content will be delivered through multiple networks.

Network virtualization: Network virtualization was used to enable the interchangeable services between network operators in order to achieve the delivery of multicast traffic. This was operated through a single virtual network while the content was delivered to users who subscribed to different networks. Most works investigated network virtualization that relates to this topic. However, there was resource allocation among virtual networks since studies on virtualization ignored multicast traffic despite different resource allocation.

Multicast traffic scheduling: In order to deliver multicast traffic to users with required QoS, there is a need for scheduling multicast services within virtual networks. These take into account the QoS requirement for each user for group selection and rate optimisation at the base station.

One of the principle research challenges in heterogeneous networks for multicast based system is to find an efficient solution to bandwidth resource allocation of multicast traffic. The solution is to allocate flows to virtual networks with the support of virtualization. This enables multiple networks to run on a single physical network. Similarly, it selects the most appropriate virtual network where multicast content can be delivered, regardless of the user's network. In the literature on heterogeneous networks [3], [19], [20], the multicast content is delivered through multiple access networks. This leads to inefficient use of bandwidth because instead of sending similar content through a single virtual network, multiple virtual networks will be needed to send the same content.

4.3. Predictive Virtual Network Selection

There are several factors that should receive our attention, including a virtual network selection. This maximises the throughput of all virtual networks to allocate flows to virtual networks. For this reason, multicast group members may receive content from any virtual network. However, to reduce bandwidth consumption, the traffic from multicast groups should be considered. The throughput of each network is predicted when the flow j is loaded on virtual network i. Thus, the multicast flow to be transmitted is assigned to virtual network

i to offer the optimum throughput. This is done through the design of a virtualized multicast service framework that enables the interchange of service delivery. This operates between multiple networks on a shareable network infrastructure. Similarly, it allocates multicast traffic in the virtualized environment for efficient use of bandwidth resources and network performance optimisation. Table 4.1 shows the matrix arrangement of flows throughput with respect to virtual networks. The matrix arrangement of demand assignments is presented in Table 4.2.

Table 4.1. Matrix of throughputs in VN s versus multicast flows.

i \ j	f_1	f_2	f_3	f_4	$\cdots\cdots$	f_n
VN_1	p_{11}	p_{12}	p_{13}	p_{14}	$\cdots\cdots$	p_{1n}
VN_2	p_{21}	p_{22}	p_{23}	p_{24}	$\cdots\cdots$	p_{2n}
VN_3	p_{31}	p_{32}	p_{33}	p_{34}	$\cdots\cdots$	p_{3n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
VN_m	p_{m1}	p_{m2}	p_{m3}	p_{m4}	$\cdots\cdots$	p_{mn}

The capacity vector of each virtual network is given by $B = \left[b_{1,}, b_2, b_3, b_4, \ldots, b_m\right]$.

Table 4.2. Matrix of demand assignments.

i \ j	f_1	f_2	f_3	f_4	$\cdots\cdots$	f_n
VN_1	r_{11}	r_{12}	r_{13}	r_{14}	$\cdots\cdots$	r_{1n}
VN_2	r_{21}	r_{22}	r_{23}	r_{24}	$\cdots\cdots$	r_{2n}
VN_3	r_{31}	r_{32}	r_{33}	r_{34}	$\cdots\cdots$	r_{3n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
VN_m	r_{m1}	r_{m2}	r_{m3}	r_{m4}	$\cdots\cdots$	r_{mn}

4.4. Multicast Service Virtualization Framework

Traditionally, multicasting enabled network technologies offer new advantages to network operators. Multiple virtual networks can benefit from each other in the context of bandwidth sharing. Noticeably, multicast services virtualization in WiMAX networks is a good example of activity. This can lead to the emergence of efficient bandwidth use for multicast services, as stated previously. However, the main issue in virtualized environments is the allocation of multicast traffic to virtual networks. This is done to use bandwidth efficiently. This section describes the multicast service virtualization framework. It distinguishes between heterogeneous networks in non-virtualized environment from heterogeneous networks in virtualized environment. The example of heterogeneous networks in non-virtualized environment is shown in Figure 4.1, where network operators A, B and C own their respective services. Thus, with this type of framework, subscriber stations from A will not receive content from B and C and vice versa since they are totally separated. If the same content is delivered to subscribers of A, B, and C, it will be delivered through multiple networks. These three networks are implemented in three different physical infrastructures with separate hardware.

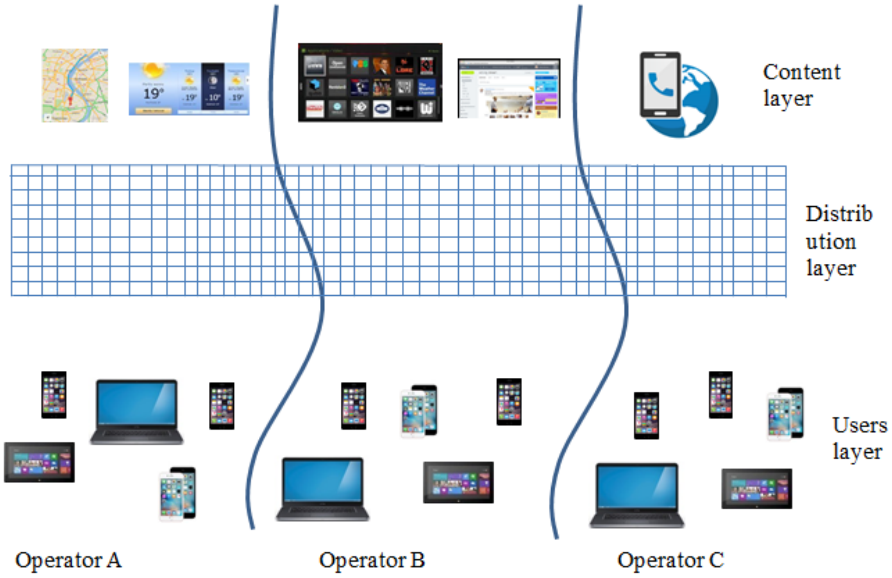


Figure 4.1. Non-virtualized service scenario.

The objective of this thesis was to design virtualization of multicast service framework that ensures efficient management by enabling network operators to deliver multicast content through a single virtual network. It is assumed that the network provider and the service provider form an entity. Thus, Figure 4.2 shows the heterogeneous framework design in a virtualized environment, on a single physical network. The framework is composed of A, B, and C networks. Users may access any content and use any resource, regardless of the network they are subscribed to. A WiMAX network consists of one or more network providers, and network operators are used to run most business entities such as access and service provision. Thus, multicast service virtualization provides a solution to the flow allocation problem by enabling efficient bandwidth management and better network performance. With the help of virtualization, the example in Figure 4.2 shows three created virtual networks running on a single physical network. This is to avoid three physical networks running on different physical network infrastructures. With the use of virtualization, three virtual networks are created and run on a single physical network.

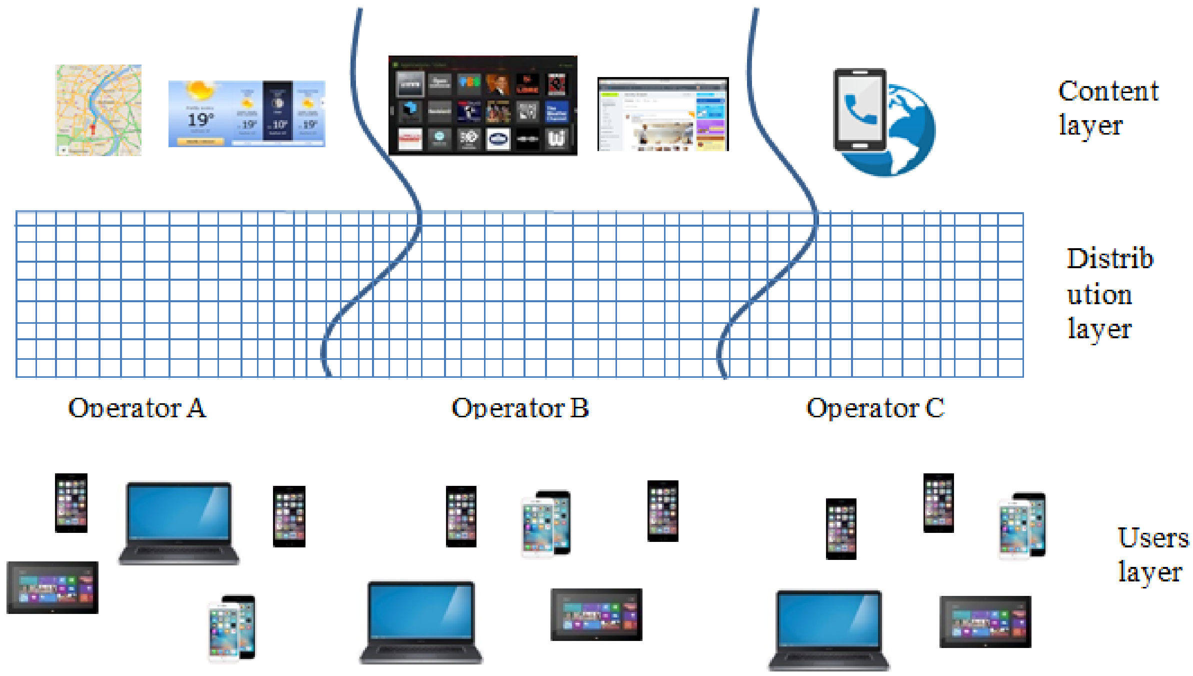


Figure 4.2. Virtualized services scenario.

The software instances represent physical networks. It is an outstanding advantage of virtualization because the base station would need to be virtualized to lodge in a full virtualization environment. This thesis argues for virtualization of multicast services and the allocation of multicast services with multicast traffic in virtual networks. Thus, subscribers from virtual networks may request content regardless of their original network. The proposed multicast service virtualization architecture is presented in Figure 4.3. This figure shows virtualized network elements like network equipments (routers) and wireless access equipments (WiMAX base stations). Similarly, there is a virtual network manager that controls the routers and determines to which virtual network the traffic should be forwarded. The virtual network manager is configured in advance and used for the management of network bandwidth reserved for various virtual networks. Then it selects the virtual network through which the content of a multicast group should be sent. In addition, the application controller communicates with the central virtual network manager to facilitate traffic allocation to virtual networks. In this way the content requested by the user is directly assigned to a selected virtual network for efficient bandwidth management.

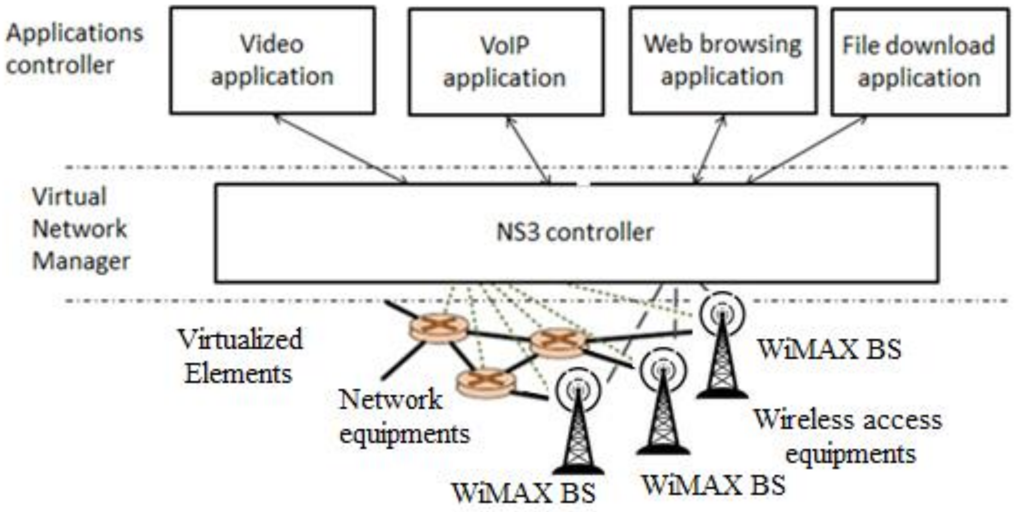


Figure 4.3. Network virtualization model in NS-3.

4.5. Multicast Service Virtualization Architecture

The multicast service virtualization enables the interchange of multicast content among network operators. In the heterogeneous multicast based system, transport plane and control plane provide the efficient delivery of multicast content. This section describes content request from multicasting groups and content distribution to multicasting groups.

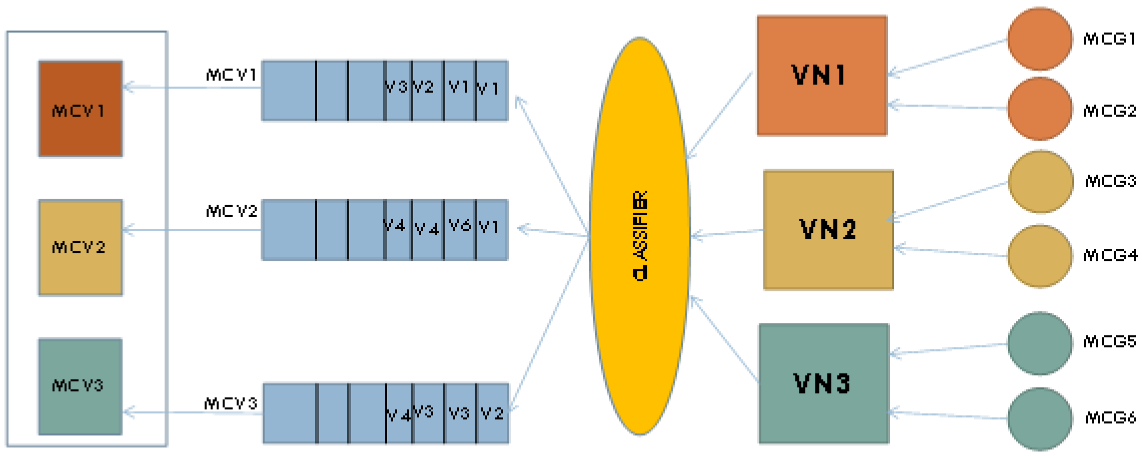


Figure 4.4. Control plane for content request from multicasting groups.

This thesis has only focused on the transport plane: that is in charge of content delivery to users through the virtual networks. Figure 4.4 shows the control plane for the content request from multicasting groups. It is divided into four stages. The first stage is Multicast Groups (MCGs) that is composed of multicast groups members. Each multicast group member requests their respective content from the VN stage. The VN stage is composed of multiple virtual networks that are responsible for sending the users' requests to the classifier stage. The classifier stage classifies these requests according to QoS requirements, and sends them to the Multicast Virtual Servers (MCV) stage that is composed of server queues. In the server queues, requests are given the name of the virtual networks from which they originate. Such queues are $v_1, v_2, \cdots, v_n$; n being the number of virtual networks. Before being processed, requests are put into their respective server queues. Multicast content is stored in multicast servers, as shown in Figure 4.4. Obviously, users who join a multicast group will request multicast content. Requests are queued in the server after being classified according to the content's location. Nevertheless, the requests are from different virtual networks.

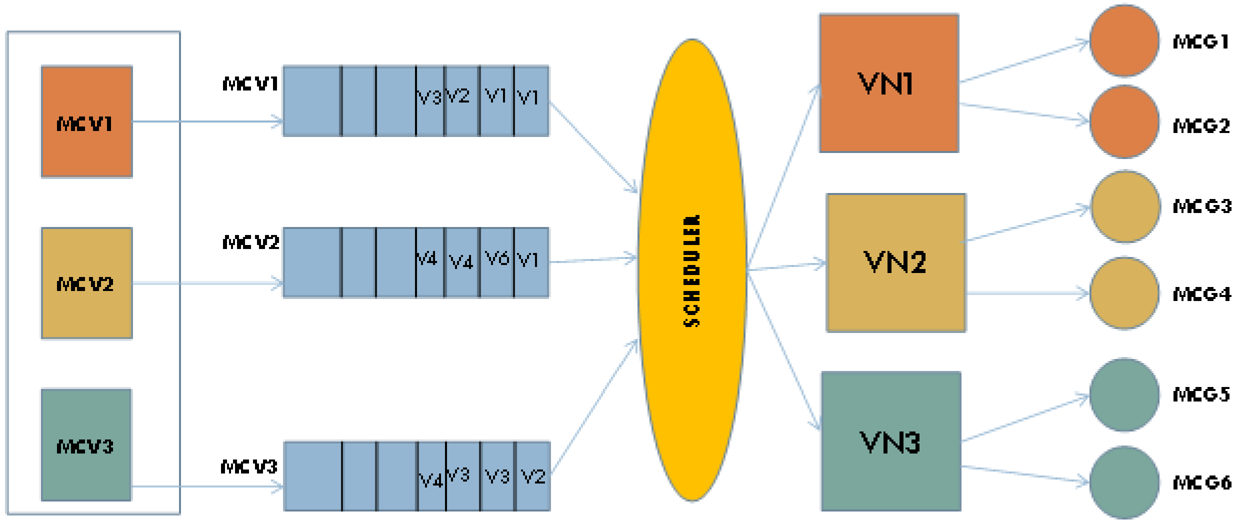


Figure 4.5. Transport plane for distribution to multicasting groups.

The data plane in Figure 4.5 hereafter confirms how the content is delivered from server to user destination. Thus, multicast content is queued in delivery server queues to be transmitted to multicast groups. First, the virtual network manager selects the virtual network through which the content will be delivered. Second, the virtual network manager determines the sequential order of the content delivery. This is done in an optimised way for efficient bandwidth management and to maximise the network throughput. The transport plane from content distribution to multicasting groups is presented in Figure 4.5. It is divided into four stages, as for the control plane.

The stage of MCV usually provides the content to MCG stage that is composed of various users. Thus, during content distribution, the content is first put in its respective server queues $v_1, v_2, \cdots, v_n$ (n is the number of virtual networks) based on how they are classified from the control plane. During transmission time, the scheduler stage selects the distribution sequence of content from the server to respective Virtual Networks (VN) to deliver the content to respective multicast groups. Figure 4.6 shows the flowchart of the control plane for content distribution from multicasting groups at different stages.

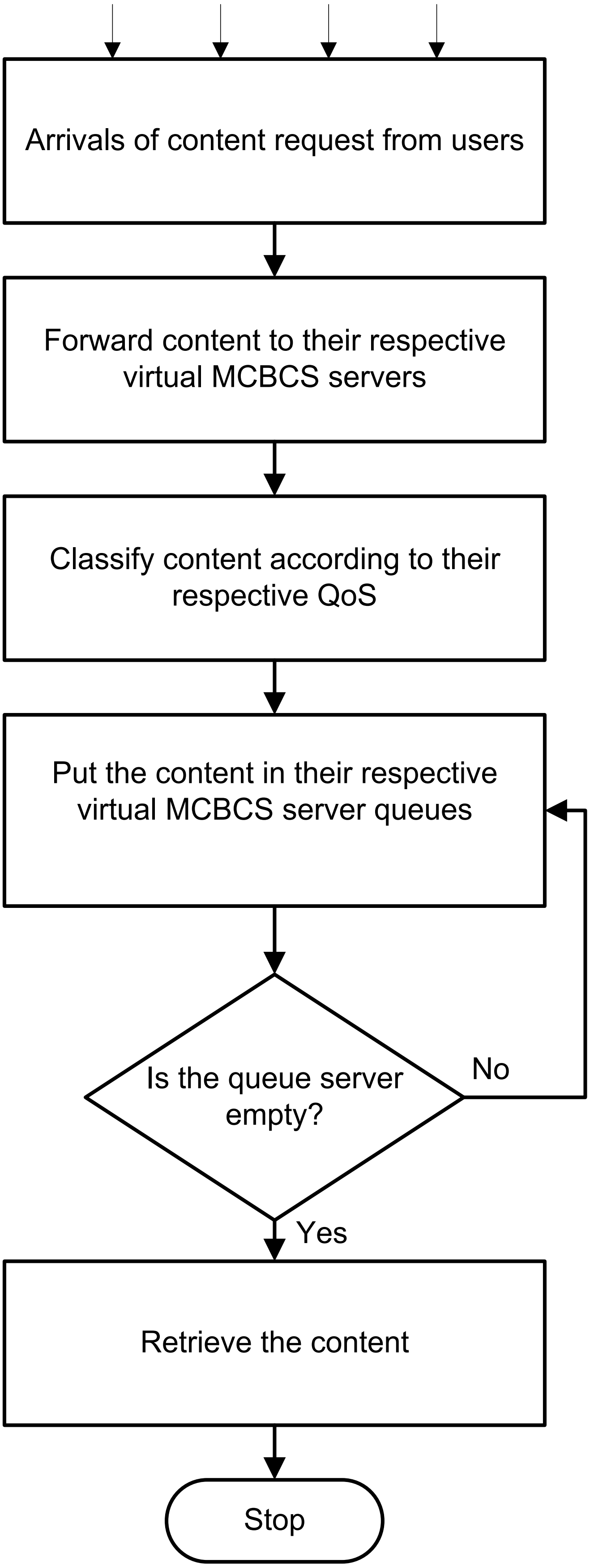


Figure 4.6. Content request flowchart.

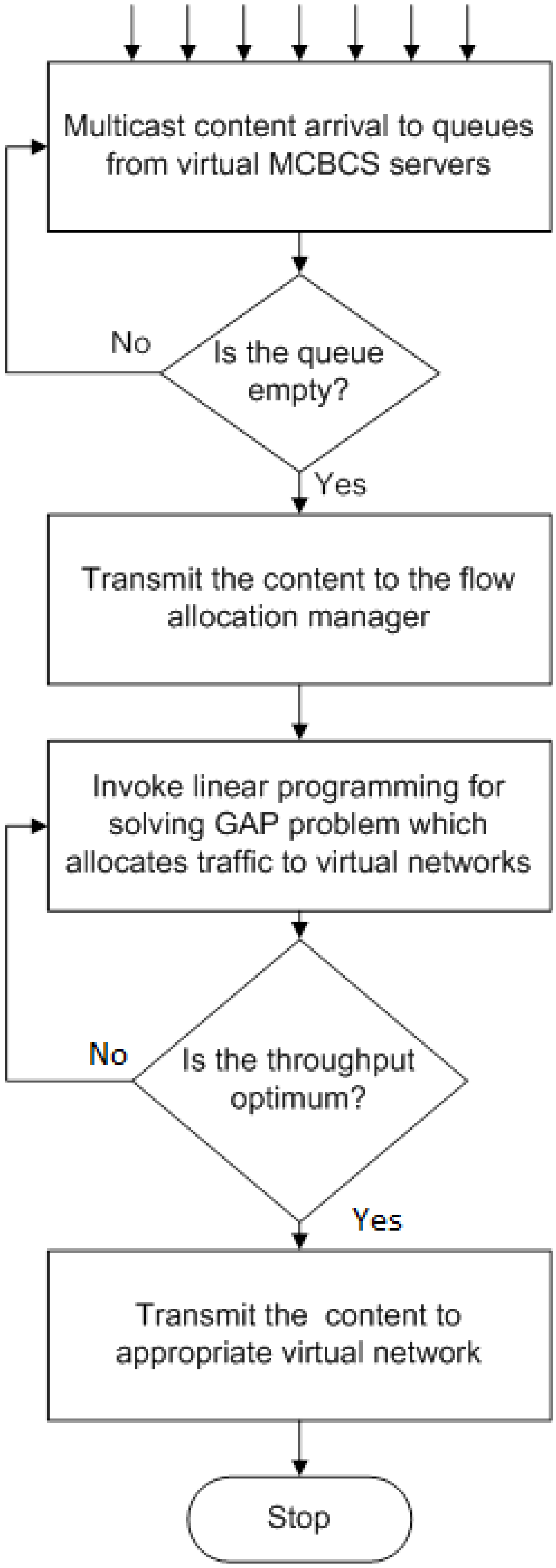


Figure 4.7. Flowchart of transport plane for distribution of multicast content.

Figure 4.7 shows a transport plane flowchart that describes the various steps whereby the data are delivered from source to their destinations. This compromises multicast group users. The multicast content is sent from the virtual MCBCS server, and then the virtual network manager invokes linear programing to allocate flows to their appropriate virtual networks.

4.6. Virtualized MCBCS Mathematical Modelling

In this section, virtualization of multicast services is modelled. The model involves multicast flows, virtual networks, and the bandwidth of individual virtual networks. This thesis aimed to allocate multicast traffic efficiently without going beyond the available bandwidth. Thus, the model solution should find the optimum throughput—denoted by P—by allocating the flows to virtual networks. The main restriction is the bandwidth of each network.

The flow allocation problem can be formulated as a Generalized Assignment Problem [99]. Mathematically, the GAP is stated as follows: Given the set of n multicast flows, $F = \{f_1, \cdots, f_n\}$, and the set of m virtual networks $VN = \{VN_1, \cdots, VN_m\}$, with $p_{ij}(t)$ the throughput of multicast flow j if assigned to be transmitted by virtual network i at time t; $r_{ij}(t)$, the bandwidth that a multicast flow j will consume, once assigned to the virtual network i and the set of bandwidths in the virtual networks $B = \{b_1, \cdots, b_m\}$.

The challenge is to assign each multicast flow to a single virtual network to optimise the bandwidth use, without assigning to any virtual network a total demand greater than its capacity.

The fact that j^{th} flow brings the throughput p_{ij} to the network i contributes to the whole throughput with the quantity $p_{ij} x_{ij}$. Therefore, the whole throughput is expressed as in (4.1).

Maximize:

$$\mathcal{P} = \sum p_{ij} x_{ij} \tag{4.1}$$

When the flow j is going through network i, it takes part $r_{ij} x_{ij}$ from the bandwidth b_i. Thus the restriction (4.2) is added as follows:

$$\sum_{j=1}^{n} r_{ij} x_{ij} \leq b_i, \qquad i \in M = \{1, \cdots, m\} \tag{4.2}$$

$$f_j \leq r_{ij} \tag{4.3}$$

Finally, the fact that a flow j can be assigned to only one network $i \in M = \{1,2,\cdots m\}$, can be expressed by (4.4).

$$\sum_{i=1}^{m} x_{ij} = 1, \qquad j \in N = \{1, \cdots, n\} \tag{4.4}$$

Let x_{ij} x be a binary variable defined by

$$x_{ij} = \begin{cases} 1, & \text{if multicast flow } j \text{ is assigned to virtual network } i \\ 0, & \text{otherwise} \end{cases} \tag{4.5}$$

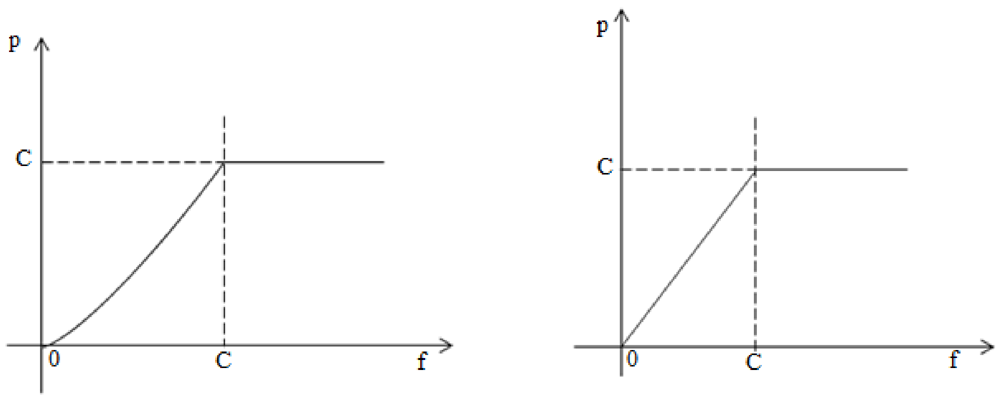
As the literature in reference [99] shows, the above maximisation problem, which is of Knapsack 0-1 type, belongs to the class of NP hard problems. Consequently, as the size and number of flows expands and the number of virtual networks increases, the computation time grows significantly. To avoid this drawback and, moreover, to obtain optimal results in flow assignment, the thesis proposes the Mixed Integer Linear Programing method to solve the GAP problem that is explained in detail in Section 4.8. However, to adapt the Knapsack problem to that method requires additional steps that are described in Section 4.7 and 4.8.

4.7. Service Throughput Considerations

All variables involved in the model, including throughput, should be defined and computed to solve the GAP problem. For estimation of the throughput of a multicast group, virtual networks capacities and multicast flows rates are considered. These are elements of the flow allocation model. Figure 4.8 shows two cases of the network behaviour, that is, throughput versus multicast flow rates. Similarly, it shows the behaviour of flows versus network capacities. Figure 4.8 (a) shows that if the flow size increases, the throughput grows exponentially. If the flow size reaches the network capacity, the network is saturated. Thus, the throughput becomes constant at the saturation value, regardless of the size value of the flows. Figure 4.8 (b) shows the flow rate and throughput move. As the flow rate increases, the throughput equally increases linearly. When the flow size reaches the capacity of the network, the network is saturated and the throughput becomes constant at a particular value of the network capacity. In this thesis, the throughput estimated that while a flow j is assigned to the virtual network, i is calculated as

$$p_{ij} = \begin{cases} f_j \cdot (1-\varepsilon), & \text{if} \quad f_j < C_i \\ \dfrac{\beta \cdot C \cdot f_i}{|C_i - f_i|}, & \text{if} \quad f_j > C_i \end{cases} \tag{4.6}$$

where C_i is the bandwidth capacity of a virtual network i, and f_j is the rate of flow j. Based on the experimentation in the course of this research project, ε was chosen to be 0.04 and β was chosen to be 0.14. In chapter 5 this equation (4.6) is validated using NS-3 simulation, and its figure shows that it is a logarithmic function which grows exponentially. The demands of flows on each virtual network is given by $D_{ij} = C_i \cdot \alpha_{ij}$, $\alpha_{ij} \in (0,1)$. Thus, to determine D_{ij}, α_{ij} should be known and α_{ij} is determined by the application broken into classes as shown in Table 4.3. The WiMAX Forum has established guidelines for the maximum amount of latency or delay that would permit these applications to operate acceptably as follows.



(a) Logarithmic case (b) Linear case.

Figure 4.8. Average throughput versus flow rate.

Table 4.3. QoS classes characteristics [6].

S/N	QoS classes	Application	Bandwidth Guideline		Latency Guideline		Jitter Guideline	
1	UGS	Multiplayer Interactive gaming	Low	50-85 Kbps	Low	<25 ms	NA	
2	ertPS	VoIP &Video conference	Low	32 to 64 Kbps	Low	<160 ms	Low	<50 ms
3	rtPS	Streaming media	Low to High	10 -384 Kbps	NA		Low	<100 ms
4	nrtPS	Web browsing & instant messaging	Mode - Rate	10 kbps to 2 Mbps	NA		NA	
5	BE	Media content Downloads	High	>2 Mbps or >500 Kbps	NA		NA	

As expected, to determine α_{ij}, virtual networks have been associated with their respective cost. Three network metrics have been considered: delay, latency and jitter. The values in

Table 4.3 was used to derive data in Table 4.4. The table shows all metrics used except the delay metric. However, this is because latency relates to delay. Delay is the time it takes a packet to be transmitted from the transmitter to the receiver, while the latency is the time a packet takes to make a round trip. Table 4.4 has been used to assign binary values to each metric, based on the relevance of the metric to determine the cost α_{ij} values. The binary value zero means that the QoS parameter represented by zero is irrelevant, and the QoS parameter represented by one is relevant. The binary table leads to the calculation of α cost values. The α cost values are associated with a QoS class in Table 4.4. Each QoS class corresponds to a virtual network.

Table 4.4. Cost value Computation.

Class	Delay	Jitter	Latency	α
1	0	0	0	0.15
2	0	0	1	0.25
3	0	1	0	0.35
4	0	1	1	0.45
5	1	0	0	0.5
6	1	0	1	0.65
7	1	1	0	0.75
8	1	1	1	0.85

The values of cost set in Table 4.4 were linearized to obtain five existing QoS class in WiMAX, and this resulted in the demands of each virtual network as shown in Figure 4.9.

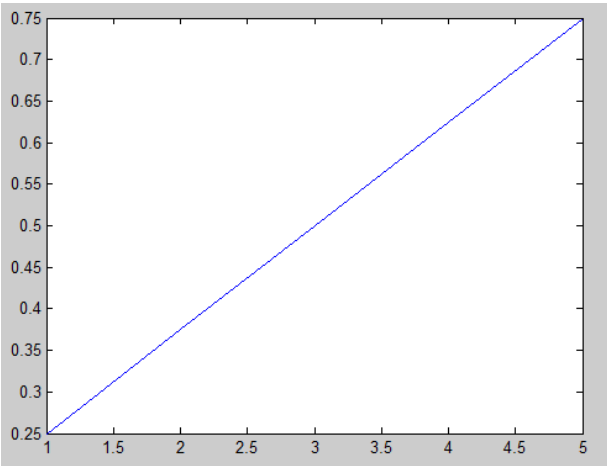


Figure 4.9. Linear distribution of α values

The values of cost obtained range from 0.15 to 0.85 because $\alpha \in (0,1)$. The lowest value of cost obtained from the table is 0.15, and the highest is 0.85. Value 1 was not considered because it represents a class with losses, delay, and jitter. The costs of different virtual networks are shown in Table 4.5 hereafter. They reflect different multicast flows that are loaded to virtual networks.

Table 4.5. Flows cost in virtual networks

	f_1	f_2	f_3	f_4	f_5
$\mathrm{VN}_i, i \in \overline{1,5}$	0.25	0.375	0.5	0.6125	0.75

Five flows were considered in Table 4.5 because WiMAX supports five different QoS classes. These flows were chosen to represent each of the five QoS class. The number of virtual networks was chosen so that it would not be too big. Similarly, the number is not to be too small since, as the number of virtual networks increases, the network performance in terms of throughput decreases.

In the GAP model the values from Table 4.5 are used where each α_{ij} cost value is multiplied by the corresponding network capacity C_i to obtain the demand of flow on the virtual network. Demands are thus functions that depend on QoS class, conditional on which VN they are delivered to, and they can be expressed as $D_{ij} = D_{ij}(QoS \setminus VN_i)$. Furthermore, at the base station side the demand for capacity from each virtual network is based on the standard values of the WiMAX Forum, as shown in Table 4.6. Only downlink data rates for 5MHz and 10 MHz bandwidth of mobile WiMAX standard IEE 802.16e were considered because multicast service is a downlink transport [100]. Thus, the data rates in Table 4.6 are given by various modulation and coding schemes supported by WiMAX. It shows the modulation type, and Convolutional Turbo Code (CTC) rate for Quadrature Phase Shift Keying (QPSK) ½ with repetition rate 6x, 2x, 1x. Similarly, it gives the convolutional code of other QPSK and Quadrature Amplitude Modulation (QAM) with different code rates. The throughput that each multicast flow can provide on each network, once loaded on that network, is computed. The GAP problem is solved as the Mixed Integer Linear Programing that selects a flow to transmit on the virtual network.

Table 4.6. Data rates with partial usage of sub-channels (PUSC) [40]

Modulation and code rate	**5 MHZ channel**	**10 MHZ channel**
	Downlink data rate (Mbps)	**Downlink data rate (Mbps)**
QPSK 1/2 CTC,6x	0.53	1.06
QPSK 1/2 CTC,4x	0.79	1.59
QPSK 1/2 CTC,2x	1.58	3.17
QPSK 1/2 CTC,1x	3.17	6.34
QPSK 3/4 CTC	4.75	9.50
16QAM 1/2 CTC	6.34	12.67
16QAM 3/4 CTC	9.50	19.01
64QAM 1/2 CTC	9.50	19.01
64QAM 2/3 CTC	12.67	25.34
64QAM 3/4 CTC	14.26	28.51
64QAM 5/6 CTC	15.84	31.68

4.8. Multicast Flow Allocation Solution

The generalized assignment problem was formulated to solve the assignment problem of allocating multicast flows to virtual networks. To allocate flows efficiently to virtual networks, the Mixed Integer Linear Programing method was proposed as this solves the GAP problem that assigns binary digit 1, whenever a flow is allocated to the virtual network and otherwise digit 0. The following procedure was used to solve the GAP problem in MATLAB by applying MILP method. P is the optimum network throughput feasible solution, B is the set of bandwidths in the virtual networks, and R is the set of bandwidth that a multicast flow j consumes once assigned to virtual network i. X is the set of binary values which assigns binary digit one when a flow j is allocated to virtual network i.

$$P = \begin{vmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mn} \end{vmatrix} \tag{4.7}$$

$$R = \begin{vmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{vmatrix} \tag{4.8}$$

$$B = [b_1, \cdots, b_m]^T \tag{4.9}$$

$$X = \begin{vmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{vmatrix} \tag{4.10}$$

Vectorization of matrices **P**, **R**, and **X**.

$$P = [p_{11}, \cdots, p_{1n}; p_{21}, \cdots, p_{2n}; p_{m1}, \cdots, p_{mn}]^T \in \Re^{m \times n} \tag{4.11}$$

$$\tilde{R} = [r_{11}, \cdots, r_{1n}; r_{21}, \cdots, r_{2n}; r_{m1}, \cdots, r_{mn}]^T \in \Re^{m \times n} \tag{4.12}$$

$$x = \begin{bmatrix} x_{11} \\ x_{12} \\ \vdots \\ \vdots \\ x_{mn} \end{bmatrix} \in \Re^{mn} \tag{4.13}$$

The previously described assignment model becomes:

$$\begin{aligned} \mathcal{P} = \sum p_{ij} x_{ij} &= p_{12} x_{12} + p_{12} x_{12} + \cdots + p_{1n} x_{1n} + p_{21} x_{21} + p_{22} x_{22} + \\ &\cdots + p_{2n} x_{2n} + p_{m1} x_{m1} + p_{m2} x_{m2} + \cdots + p_{mn} x_{mn} = Px \end{aligned} \tag{4.14}$$

$$\sum_{j=1}^{n} r_{ij} x_{ij} \le b_i, \quad i = 1, \cdots, m \tag{4.15}$$

$$\begin{cases} r_{11}x_{11} + r_{12}x_{12} + \cdots + r_{1n}x_{1n} \le b_1 & (i=1) \\ r_{21}x_{21} + r_{22}x_{22} + \cdots + r_{2n}x_{2n} \le b_2 & (i=2) \\ \vdots \quad \vdots \quad \cdots \quad \vdots \quad \vdots \; \vdots & \vdots \\ r_{m1}x_{m1} + r_{m2}x_{m2} + \cdots + r_{mn}x_{mn} \le b_m & (i=m) \end{cases} \tag{4.16}$$

To transform it into a standard linear programing formulation:

$$Ax \le B; B = [b_1, \cdots, b_n]^T \tag{4.17}$$

construct:

$$A = \left(\begin{array}{ccccc|ccccc|c|ccccc} r_{11} & \dots & \dots & \dots & r_{1n} & 0 & \dots & \dots & \dots & 0 & \dots\dots & 0 & \dots & \dots & \dots & 0 \\ 0 & \dots & \dots & \dots & 0 & r_{21} & \dots & \dots & \dots & r_{2n} & \dots\dots & 0 & \dots & \dots & \dots & 0 \\ 0 & \dots & \dots & \dots & 0 & 0 & \dots & \dots & \dots & 0 & \dots\dots & 0 & \dots & \dots & \dots & 0 \\ & & \vdots & & & & & \vdots & & & \vdots & & & \vdots & & \\ 0 & \dots & \dots & \dots & 0 & 0 & \dots & \dots & \dots & 0 & \dots\dots & 0 & \dots & \dots & \dots & 0 \\ \underbrace{0 \quad \dots \quad \dots \quad \dots \quad 0}_{i=1} & & & & & \underbrace{0 \quad \dots \quad \dots \quad \dots \quad 0}_{i=2} & & & & & \dots\dots & \underbrace{r_{m1} \quad \dots \quad \dots \quad \dots \quad r_{mn}}_{i=m} & & & & \end{array} \right) \tag{4.18}$$

$$\sum_{i=1}^{m} x_{ij} = 1, \; j = 1, \cdots, n \tag{4.19}$$

$$\begin{array}{ll} x_{11} + x_{12} + \cdots + x_{m1} = 1 & (j=1) \\ x_{21} + x_{22} + \cdots + x_{m2} = 1 & (j=2) \\ \vdots \quad \vdots \quad \cdots \quad \vdots \quad \vdots & \vdots \\ x_{m1} + x_{m2} + \cdots + x_{mn} = 1 & (j=n) \end{array} \tag{4.20}$$

To transform it into

$$A_{eq}x = b_{eq}, b_{eq} = [1, \cdots 1]_n^T \tag{4.21}$$

A_{eq} is set as

$$= \left[I_{m\times n} \middle| I_{m\times n} \middle| \cdots \middle| I_{m\times n} \right] \in \Re^{m\times(m*n)}$$

$$A_{eq} = \left[\underbrace{\begin{matrix} 1 & 0 & 0 & \ldots\ldots & 0 \\ 0 & 1 & 0 & \ldots\ldots & 0 \\ & & & \vdots & \\ 0 & 0 & \ldots\ldots & 0 & 1 \end{matrix}}_{i=1} \middle| \underbrace{\begin{matrix} 1 & 0 & 0 & \ldots\ldots & 0 \\ 0 & 1 & 0 & \ldots\ldots & 0 \\ & & & \vdots & \\ 0 & 0 & \ldots\ldots & 0 & 1 \end{matrix}}_{i=2} \middle| \begin{matrix} \ldots\ldots \\ \ldots\ldots \\ \vdots \\ \ldots\ldots \end{matrix} \middle| \underbrace{\begin{matrix} 1 & 0 & 0 & \ldots\ldots & 0 \\ 0 & 1 & 0 & \ldots\ldots & 0 \\ & & & \vdots & \\ 0 & 0 & \ldots\ldots & 0 & 1 \end{matrix}}_{i=m} \right] \tag{4.22}$$

MATLAB Solution:

- Declare the matrices, **P**, **R** and vector **B**
- Construct vectors $\widetilde{\mathrm{P}} = \mathrm{Ptilda}$, and R
- Construct matrices A, A_{eq}
- Intcon=ones(m,n)
- Use intlinprog (Ptilda, intcon, A, B, Aeq, beq, lb, ub) in MATLAB to solve the GAP problem

where

$l_b = [0,\cdots 0]^T_{m*n}$ is the lower bound, and

$u_b [1,\cdots,1]^T_{m*n}$ is the upper bound.

4.9. Multicast Bandwidth Allocation

A virtualized network environment encounters the problem of bandwidth use between virtual networks. A user sends a request to join a particular multicast group to the attached virtual network before the multicast session is established. Figure 4.10 illustrates the problem. Users are located in the same area and are anticipated to receive the same multicast flows. User 1 is attached to VN_1; users 2 and 3 are attached to VN_2; and users 4 and 5 are attached to VN_3. Conventionally, if all users request for the same content, the multicast content may be sent via all three virtual networks to the respective attached users. Consequently, this does not fully solve the bandwidth problems. This work allocates a multicast flow to a single virtual network. Similarly, it delivers the multicast content to all users in that multicast group, regardless of their attachment to virtual networks. Another challenge is the characteristics of virtual networks. These are designed to deliver differentiated QoS to multicast users who request the same contents; however they require different QoS. That is why, in this thesis, an approach to optimise the allocation of multicast flows based on QoS support of the virtual networks was developed. In the developed framework, multicast content should be provided. To optimise network performance, the throughput should be improved. It should equally reduce jitter and delay after the selection of appropriate delivery virtual networks that require awareness of virtual networks capacity.

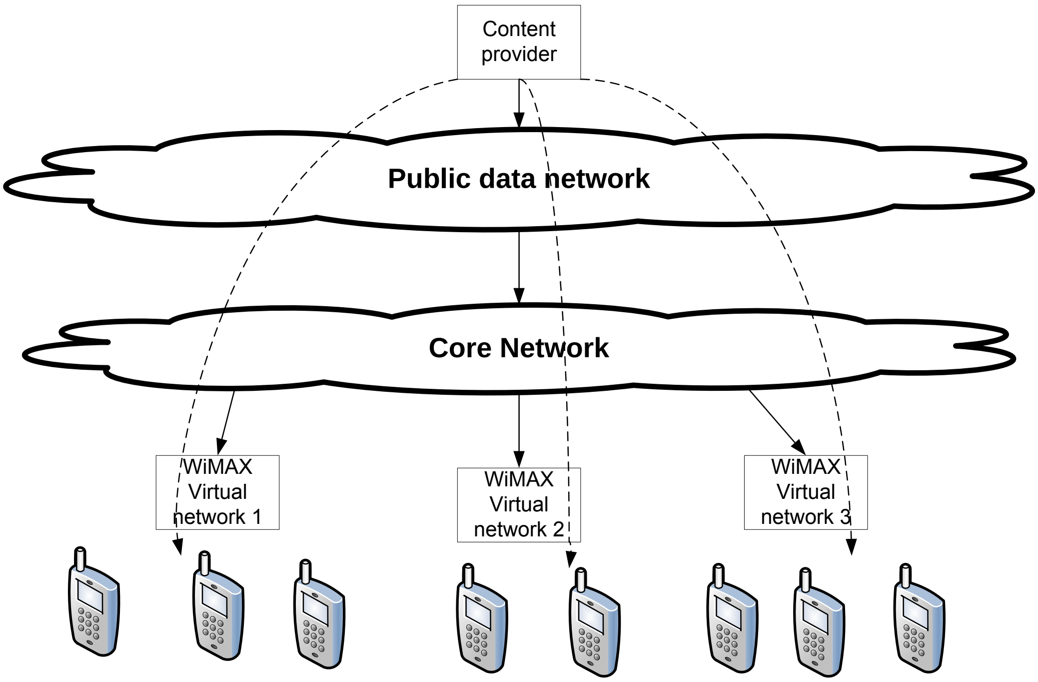


Figure 4.10. Multicast bandwidth allocation in virtualized WiMAX networks

4.10. Multicast Content Delivery

This section highlights a network controller that enables different operators to offer secure and seamless shared services to users across virtualized WiMAX networks. In virtualized environments, virtual networks should be controlled by the hypervisor to provide multicast services. In this work a virtual network manager placed on top of WiMAX networks at the ASNGW is proposed. Its function is to decide to which virtual network the multicast traffic can be allocated and enables the virtual networks to share the bandwidth [101].

Similarly, the virtual network manager enables the achievement of varied of tasks. These tasks are needed for interworking and logical link identification between virtual networks. They guarantee an efficient internetwork for operators for quality service delivery. This is done without revealing that they belong to network autonomy and, likewise, reveals any delicate information related to the network [101]. Figure 4.11 illustrates interworking of architecture of WiMAX virtual networks.

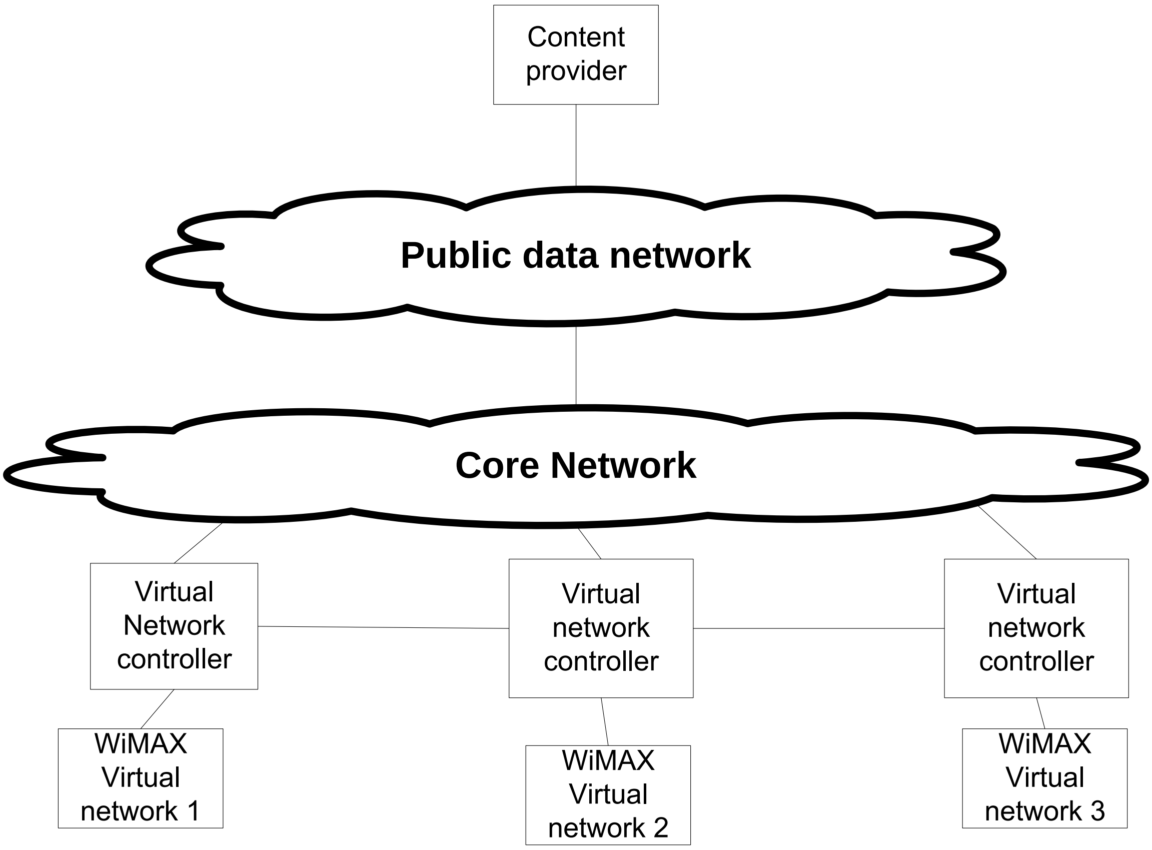


Figure 4.11. Content delivery coordination in multicast virtualization

4.11. Bandwidth Management

Bandwidth management mechanism is responsible for ensuring the efficient use of bandwidth for the transmission of multicast service within multiple virtualized networks. The current bandwidth management approaches in WiMAX networks consider that a single network operator manages bandwidth in the heterogeneous networks. This is so because the network operators need to control their bandwidth fully and are unwilling to release any information regarding load traffic outside their administration domains. Thus, the centralised entities take decisions on the bandwidth management [101].

For the optimisation of multicast services delivery, a number of methods to manage bandwidth can be used via bandwidth management algorithms. The techniques are mainly aimed at multimedia multicast services:

- Scheduling multicast service
- Network selection delivery
- Selection of QoS service

Scheduling multicast service is used by multimedia-on-demand services to optimise the set up time for multicast group. It determines the time when the required service should be transmitted [101].

Network selection delivery chooses the best virtual network for the transmission of a multicast content for a particular multicast flow. This determines which multicast flow should be assigned to which virtual network [101].

Selection of QoS service is done according to the availability of bandwidth changes of the multicast transmission QoS. This is worked out by choosing a multicast flow with an appropriate user QoS, since various multicast flows at various QoS levels are considered. It determines the QoS with which a multicast flow is served [101]. Some algorithms can be used with regard to each of the above techniques of bandwidth management. The objectives of these algorithms are to solve two problems in the perspective of multicast service virtualization in WiMAX networks.

4.12. Experimental Scenarios Evaluation for virtual network allocation.

This subsection shows the results of the allocation of flows to virtual networks to optimise the network throughput as stated in the objective of this research. GAP and MILP were used to solve the allocation problem. Three and five virtual networks were considered, and the work was to allocate flows to these virtual networks. Thus, three scenarios were set up, whereby; one flow and five flows were to be allocated to the five virtual networks, and three flows to be allocated to three virtual networks. The network performance was compared with the increase of flows size in relation to static and dynamic virtual network capacity. In static virtual network, virtual network capacities values were set to be constant throughout all the experiments. However, in the dynamic virtual network, the capacities of the three and five virtual networks varied. This variation was chosen arbitrarily since the objective was to identify the difference in the virtual network selection.

The allocation results obtained from this section were moved to the NS-3 simulator where the MILP approach was tested. Subsequently, in chapter five, the allocation considered was for three flows and three virtual networks. Choosing the three flows and virtual networks is for the sake of testing the performance of MILP approach for multimedia data (VoIP, video and data). The next part discusses experiment results of both scenarios.

Scenario 1: Static Capacity of virtual network

One flow and five virtual networks

In order to thoroughly analyse the allocation of flows to the virtual networks, the lowest possible number of multicast flows that is one flow, was considered. Since multimedia service is the content that can be delivered to users that demand high bandwidth, this motivated the report of this thesis to consider the capacity of virtual networks in terms of Mbps for the support of those services that require higher bandwidth. The network capacities of VN_1 to VN_5 are chosen to be 10, 5, 2, 4, 7 Mbps respectively.

Thereafter, using MILP, the flow is allocated to only one virtual network which is VN_5, and the throughput obtained in each case is presented. Table 4.7 shows that once the flow rate changes, the allocation remains the same except for the varying throughput. However the allocation of flows to virtual network changes when the virtual network capacity varies. The allocation results are the same for all applications such as VoIP, video clips streaming, music streaming, interactive gaming, and media content download.

Table 4.7 Achieved throughput after allocation of VoIP flows to virtual networks

Applications and their flow rate	Interactive gaming (85 Kbps)	VoIP flow (64 Kbps)	Music streaming (128 Kbps)	Video clips streaming (384 Kbps)	Media content download (500 Mbps)
Achieved throughput	81.6 Kbps	61.44 Kbps	122.88 Kbps	368.64 Kbps	480 Kbps
Selected virtual network	VN_5	VN_5	VN_5	VN_5	VN_5

Five flows and virtual networks

In the case of five flows and five virtual networks, two scenarios were considered: static virtual network capacity and dynamic virtual network capacity. The experiment was run four times with five interactive gaming flows of 85 Kbps each, five VoIP flows of 64 Kbps each, five streaming media (music) flows of 128 Kbps each, five streaming media (video clips) flows of 384 Kbps each and five media content download flows of 500 Kbps each. The obtained results of flow allocation to virtual networks in all the runs are shown in Table 4.8 and the achieved throughput for all applications on virtual networks is shown in Table 4.9.

Table 4.8. Virtual network selection for the VoIP, streaming media, web browsing, and media download applications

	Virtual network capacity in Mbps	f_1	f_2	f_3	f_4	f_5
VN_1	10	1	0	1	0	0
VN_2	5	0	0	0	0	1
VN_3	2	0	0	0	0	0
VN_4	4	0	0	0	0	0
VN_5	7	0	1	0	1	0

Table 4.9. Achieved throughput after allocation for static capacity

Applications and their flow rate	Interactive gaming (85 Kbps)	VoIP flow (64 Kbps)	Music streaming (128 Kbps)	Video clips streaming (384 Kbps)	Media content download (500 Mbps)
Achieved throughput	408 Kbps	307.2 Kbps	614.4 Kbps	1.84 Mbps	2.4 Mbps

In case of static network capacity, the above results show that the allocation of flows to virtual networks is the same for all applications.

Scenario 2: Dynamic Capacity of virtual network

To allocate flows to the virtual networks using MILP technique for dynamic network capacities, three and five flows and virtual networks were considered. In case of three virtual networks, two scenarios were presented to show that the allocation of flows to the virtual networks changes when the network capacities of the virtual networks change. On the other hand, five flows and virtual networks were also considered. In this case, four runs were presented with the variation of the network capacities, where each run considers either VoIP, media download, streaming media, or interactive gaming flow.

Three flows and virtual networks

In case of three flows and virtual networks, the network capacities considered was 2, 10 and 5 Mbps. The variations of the three network capacities were done to illustrate dynamic capacities of the virtual networks. Results of the experiment show that whenever the capacities of the network changes, the allocation of flows to the virtual networks also changes.

During the experiment, it was observed that all runs allocate the flows to virtual networks differently whenever the network capacities change. Thus, only two runs are presented in tables Table 4.10 and Table 4.11 which show the flow allocation results for three flows and virtual networks. Similarly, the achieved throughput in each case after the flow allocation is 910.08 Kbps.

Table 4.10. Virtual network selection with 2,10,5 Mbps for VN1, VN2, VN3 respectively

	Virtual network capacity in Mbps	f_1 (64 Kbps)	f_2 (384 Kbps)	f_3 (500 Kbps)
VN_1	2	0	0	0
VN_2	10	1	1	0
VN_3	5	0	0	1

Table 4.11. Virtual network selection with 2,5,10 Mbps for VN1, VN2, VN3 respectively

	Virtual network capacity in Mbps	f_1 (64 Kbps)	f_2 (384 Kbps)	f_3 (500 Kbps)
VN_1	2	0	0	0
VN_2	5	0	0	1
VN_3	10	1	1	0

Five flows five virtual networks

Five VoIP flows were set, each with a flow rate of 64 Kbps. The flow allocation results and the settings of the virtual network capacities are shown in Table 4.12. The achieved throughput result is 307.2 Kbps.

Table 4.12. Virtual network selection for the VoIP applications

	Virtual network capacity in Mbps	f_1	f_2	f_3	f_4	f_5
VN_1	10	1	0	1	0	0
VN_2	5	0	0	0	0	1
VN_3	2	0	0	0	0	0
VN_4	4	0	0	0	0	0
VN_5	7	0	1	0	1	0

Five streaming media flows were set, each with a flow rate of 128 Kbps. The flow allocation results and used virtual network capacities are shown in Table 4.13. The throughput achieved is 614.4 Kbps.

Table 4.13. Virtual network selection for streaming media applications

	Virtual network capacity in Mbps	f_1	f_2	f_3	f_4	f_5
VN_1	7	0	1	0	1	0
VN_2	4	0	0	0	0	0
VN_3	2	0	0	0	0	0
VN_4	10	1	0	1	0	0
VN_5	5	0	0	0	0	1

Five interactive gaming flows were set, each with a flow rate of 85 Kbps. The flow allocation results and used virtual network capacities are shown in Table 4.14. The throughput achieved is 408 Kbps.

Table 4.14. Virtual network selection for interactive gaming applications

	Virtual network capacities (Mbps)	f_1	f_2	f_3	f_4	f_5
VN_1	7	0	1	0	1	0
VN_2	4	0	0	0	0	0
VN_3	5	0	0	0	0	1
VN_4	2	0	0	0	0	0
VN_5	10	1	0	1	0	0

Five media download flows were set, each with a flow rate of 500 Kbps. The flow allocation results and used virtual network capacities are shown in Table 4.15. The achieved throughput is 2.4 Mbps.

Table 4.15. Virtual network selection for media download applications

	Virtual network capacities (Mbps)	f_1	f_2	f_3	f_4	f_5
VN_1	2	1	0	0	0	0
VN_2	10	0	1	1	0	0
VN_3	7	0	0	0	1	0
VN_4	5	0	0	0	0	1
VN_5	4	0	0	0	0	0

The achieved throughput for dynamic virtual network capacity in all four cases of five flows and five virtual networks is shown in Table 4.16.

Table 4.16. Achieved throughput for dynamic capacity

Applications and their flow rate	Five VoIP flows (64Kbps)	Five media download flows (128 Mbps)	Five Interactive gaming flows (85 Kbps)	Five streaming media flows (128Kbps)
Achieved throughput	307.2 Kbps	2.4 Mbps	408 Kbps	614.4 Kbps

Overall, observation from all the above results shows that where the network capacity is static, the virtual network selection and allocation are always the same. Whereas with the dynamic capacity of the virtual network, the selection and allocation of flows to the virtual network changes. Thus, the dynamic change of virtual network capacities is used to select virtual networks fairly. These allocation results, obtained from Mixed Integer Linear Programing, are moved to NS-3. This is to evaluate the network performance after the allocation of flows to virtual networks, and these are discussed in Chapter 5. The next section focuses on the group mapping of multicast flows within a virtual network.

4.13. Multicast Flow Group Mapping

As stated earlier, to provide better QoS to users who request multicast content, and after selection of the virtual networks, the multicast group scheduling and rate optimisation within a virtual network should be done. In this section, a new scheduling algorithm was designed to consider delay parameters for the selection of multicast traffic and optimum rate within a virtual network.

Denoted by p_i^{av}, let this be the average throughput of user i and G is the total number of multicast groups. N_g is the total number of subscriber stations in multicast group g, $r_{ig}(t)$ is the channel state information rate for subscriber station i in group at time t. Let $r_g^e(t)$ be the estimated rate assigned to group g at time t , and $q_{ig}(t)$ be the rate needed to achieve the required QoS for user i in the multicast group g. Then, p_{ig}^{av} is the rate calculated via statistical smoothing techniques such as the exponential moving average throughput for user i in group g.

The problem is formulated for a single virtual network composed of a single base station. This schedules multicast flows by using the information on the channel state from each subscriber station in the multicast group. Thus, QoS requirements for the multicast flows to determine the multicast group rate are considered. The rate $r_{ig}(t)$ $r_{ig}(t)$ is estimated as follows [102]:

$$r_{ig}(t) = BW \cdot \log_2(1 + SNR_i(t)) \tag{4.23}$$

where BW is the bandwidth in MHz, and SNR_i is the Signal to Noise Ratio for user i in group g at time t. The QoS needed rate $q_{ig}(t)$ is calculated as [103]

$$q_{ig}(t) = \min\left\{\max\left\{\vartheta_i, r_i^{\min}(t)\right\}, r_i^{\max}\right\} \tag{4.24}$$

where ϑ_i is the minimum average traffic requirement rate for the real-time users; $r_i^{\min}$ is the data rate requirement to ensure the QoS guarantees; and $r_i^{\max}$ is the maximum possible data rate of the real time users in time slot t, which may send packets in the queue for a single time slot.

Let the allocation of time resources schedule be defined as follows [27].

$$S_g(t) := \begin{cases} 1, \text{if the time resource is allocated to group } g \text{ at time } t \\ 0, \qquad\qquad\qquad\qquad\qquad\qquad \text{otherwise} \end{cases} \tag{4.25}$$

The updated exponential moving average throughput is given by [33]:

$$p_{ig}^{av}(t+1) = (1-\rho)\, p_{ig}^{av}(t) + \rho r_g^e(t) S_g(t) 1_{\left\{r_{ig}(t) \le r_g^e(t) \le q_{ig}(t)\right\}} \tag{4.26}$$

where ρ is a scale parameter that represents the number of slots the user i in group g will receive a rate of $r_g^e(t)$, but only if the group g is selected, and its channel state information rate $r_{ig}(t)$ is greater than or equal to $r_g^e(t)$, and the channel state information rate $r_{ig}(t)$ is less than or equal to the rate $q_{ig}(t)$, as required by QoS constraints. Consider the aggregate throughput of group g at time t denoted by $P_g(t)$ [27] and the aggregate rate of all users in group g at time t by $\varphi_{g,t}(f)$ where the base station in a virtual network transmits at rate f, according to reference [27].

$$P_g(t) = \sum_{i=1}^{N_g} P_{ig}(t) \tag{4.27}$$

$$\varphi_{g,t}(f) = \sum_{i=1}^{N_g} f \cdot l(t)_{\{f \le r_{ig}(t)\}} \cdot k(t)_{\{f \ge q_{ig}(t)\}} \tag{4.28}$$

further, one gets

$$\varphi_{g,t}(f) = \sum_{i=1}^{N_g} f \cdot \min\left\{l(t)_{\{f \le r_{ig}(t)\}}, k(t)_{\{f \ge q_{ig}(t)\}}\right\} \tag{4.29}$$

Where

$$l(t) = \begin{cases} 1, \text{if } \; f \le r_{ig}(t) \\ 0, \quad \text{otherwise} \end{cases} \tag{4.30}$$

And

$$k(t) = \begin{cases} 1, \text{if } \; f \ge q_{ig}(t) \\ 0, \quad \text{otherwise} \end{cases} \tag{4.31}$$

Equations (4.26), and (4.29) were defined in [33] for multicast flow scheduler. This type is an intra-class scheduler of traffic flows. In [27], the authors have considered a multicast group rate selection, where the aggregate rate depends only on the maximum information rate of each subscriber station. However, QoS demands were not considered when selecting the multicast flow rate. Thus, reference [33] has taken into consideration the multicast flow rate scaling and both the channel state rate for each subscriber station and the QoS demands for multicast flows.

4.13.1. Group Rate Selection

The estimated rate assigned to group g at time t to satisfy QoS and channel state constraints is [33]:

$$r_g^e(t) = \arg\max_f \sum_{i=1}^{N_g} f \cdot \min\left\{ l(t)_{\{f \le r_{ig}(t)\}}, k(t)_{\{f \ge q_{ig}(t)\}} \right\} \tag{4.32}$$

Let us denote the value of f which maximises $\varphi_{g,t}(f)$ as f^*.

A base station in a virtual network chooses to serve the group $g(t)$ at rate $r_g^e(t)$, given by [33]

$$g(t) = \arg\max_{1 \le g \le G} \frac{\varphi_g\left(r_g^e(t)\right)}{P_g(t)} \tag{4.33}$$

which is denoted by g^*

4.14. Software Representation of MCBCS

In software representation of the multicast flow scalability, two aspects were considered: intra-class and interclass scheduler types of scheduling algorithms, and the hierarchical architecture of these schedulers working jointly. As shown in Figure 4.12, the interclass Priority-Based scheduler is used to schedule multicast traffic according to priority starting from UGS, rtPS, nrtPS and BE. Then, an intra-class Proportional fair scheduler (PFS) is used among UGS multicast traffic flows between rtPS multicast connections. Similarly, an inter-class Proportional Fair scheduler is used between nrtPS and BE multicast traffic flows. In addition, Figure 4.12 shows the difference between the scheduling of QoS classes which are UGS, rtPS, nrtPS, and BE.

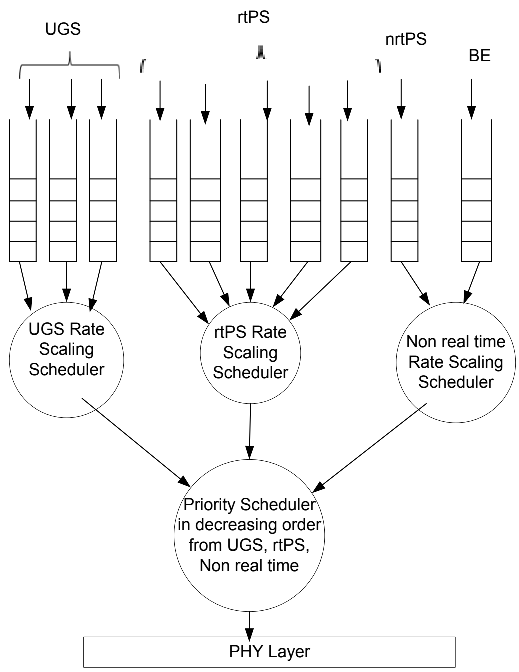


Figure 4.12. Scheduling hierarchy for flow rate scaling.

The pseudo code of flow rate scaling, the rate selection and how it can be used in the scheduling of multicast traffic is shown in Figure 4.13. The pseudo code describes the scheduling of UGS class; the pseudo code for scheduling all the remaining QoS classes, which are rtPS, nrtPS, and BE, is the same as the pseudo code for UGS QoS class.

Select UGS multicast connections
while UGS connections Do
if UGS connections has packets to transmit and latency check are satisfied
  for modulation 1 to 7
    for multicast group to G
      Compute φ *according to* (4.29)*;*
      Compute r_g^e *according to* (4.32);
      Compute g *according to* (4.33);
      Schedule g^*
    end For
  end For

Figure 4.13**.** Multicast Scheduling traffic pseudo code.

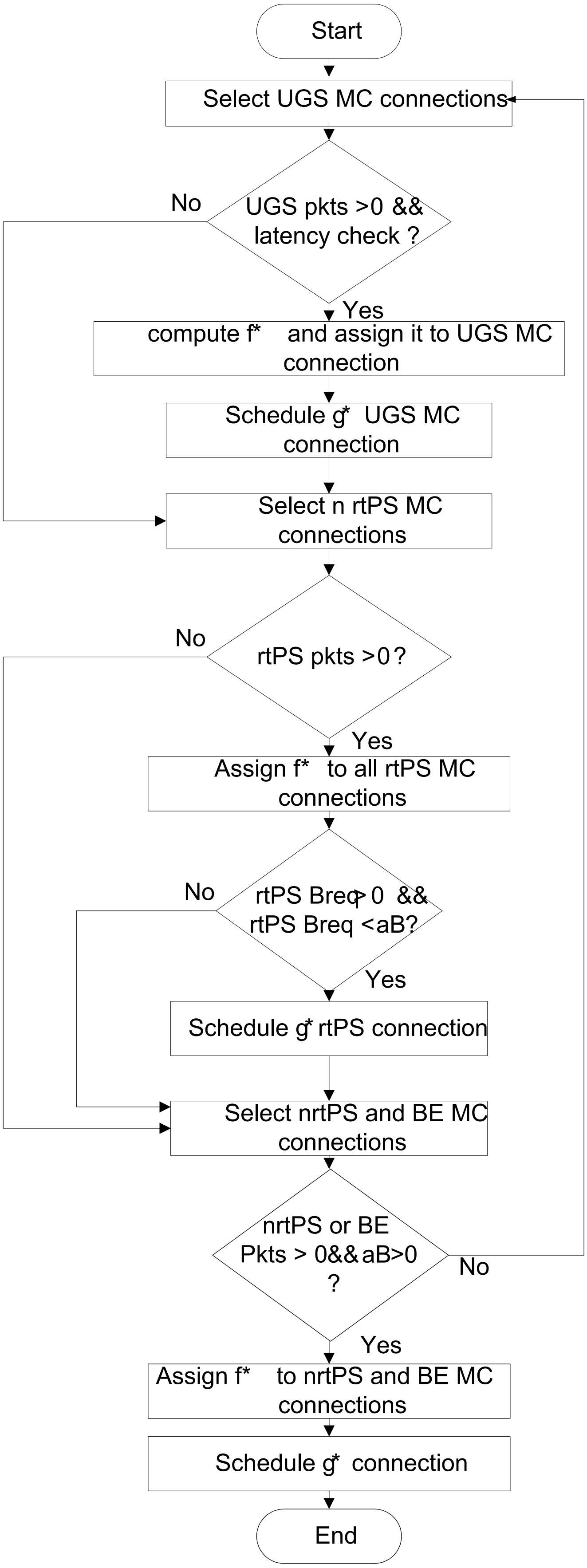


Figure 4.14. MCBCS bandwidth sharing flow chart

The flow chart in Figure 4.14 shows the logic of how this new flow scheduler will be implemented. The scheduler starts with the selection of UGS multicast flow. It checks for connections which have packets and delay constraints as this type of class is delay sensitive. Then it sets f^* transmission rate to each multicast connection and chooses the group to assign the connection according to Equation (4.33). After scheduling all UGS connections, the scheduler allocates rtPS flows. First, the scheduler checks whether the connections have packets and the transmission rate f^* is assigned to the connections that have packets. Second, it follows the step of checking for the bandwidth availability constraints. Then, it schedules all rtPS connections by using Equation (4.33).

Unlike the previous steps, the scheduler selects two types of flows at the same time, for instance nrtPS and BE connections. The scheduler starts by checking whether there is any packets in the connections and it then maps the transmission rate f^* to the connections. After checking, it assigns f^* rate to all rtPS and BE connections, and checks whether there is any available bandwidth. Then it schedules f^* connection according to Equation (4.33).

4.15. Summary

This chapter has analysed and interpreted the design specification of virtualization of multicast service framework. Virtualization of multicast service enables the sharing of multicast services among users from multiple networks. It equally facilitates efficient use of bandwidth by delivering the content demand through a single virtual network on a single channel. The design of multicast virtualization was first proposed to enable the interchanges of multicast content between multiple virtual networks. The advantage is that it allows the cooperation of multiple networks within the same environment.

Then a mathematical model that enables the sharing and efficient use of bandwidth was devised to monitor the delivery of multicast traffic among virtual networks. Many parameters were chosen to be used in GAP for the development of the model. These had to be determined in the course of flow allocation to virtual networks. Thus, a new theory that predicts the values close to the real throughput has been proposed. A description of the implementation of MILP, which involves the development of code, has been set up to solve the allocation problems. This was used to conduct experiments in MATLAB. The experiment focused on how to optimise the throughput for flows allocation and achieve fairness in the allocation of flows to virtual networks. However, multicast resource discovery and allocation can be used to illustrate the virtual network manager. This determines to which virtual network the traffic should be delivered. Nevertheless, resource management determines the delivery of multicast service after predicting the network throughout.

Finally, multicast flow rate scaling closes this chapter. It determines the optimum transmission rate for the multicast group and which multicast group should be scheduled in order to provide better QoS to users. The next chapter presents the implementation of WiMAX model in NS-3.

CHAPTER 5

5 MULTICASTING VIRTUALIZATION IMPLEMENTATION

5.1. Introduction

This chapter focuses on the implementation of flow allocation problem analysed in chapter 4, where MILP was used to solve flow allocation problem. To evaluate the performance of flow allocation solution that was obtained from MILP, the results obtained after using MILP was considered. That is in regard to virtualization of multicast service framework implemented using NS-3 simulator. Similarly, this chapter summarises the implementation of the virtualization of multicast service framework and its performance evaluation. NS-3 simulator and its suitability with virtualization of multicast services in WiMAX network are explained. The chapter elaborates the emulation topology and software representation for multicast virtualization. The performance measures and simulation setup that have been used are highlighted in this research.

5.2. NS-3 Simulator

The virtualization of multicast services simulation model developed in this work is implemented and tested using the NS-3 software environment. NS-3 software was chosen because the focus of this thesis is virtualization of multicast services in WiMAX networks. Thus, the choice of the simulator should enable the simulation of WiMAX network features. NS-3 is an open source simulation tool that provides several network and application performance management solutions. Similarly, NS-3 is a discrete-event network simulator in which the simulation core and models are implemented using C++; this is licensed under the GNU GPLv2 license and accessible to the public. As an open source, NS-3 has the ability to be programmed and to create virtual networks [104]. NS-3 is built as a library that can be statically or dynamically linked to C++ and Python main programing. This defines the simulation topology and starts the simulator. It has the capabilities for analysis and

debugging. Some of its key features include a model library involving many protocols, nodes implementations and object oriented programing.
Furthermore, NS-3 offers models of the network's data packets function and a simulation engine for users to conduct networking experiments. Additionally, NS-3 is used as a network simulator because it performs more complex studies that cannot be performed in real systems. This is set to study a system's behaviour in a highly controlled environment [104].

The features which distinguish NS-3 from other network simulators are described in [104] as follows:

- NS-3 is developed with a number of libraries assembled with other external software.
- NS-3 is constructed of many modules. It is not like other platforms of simulation that offer users a single and integrated environment of graphical user interface. It is in this environment that all the experiments are carried out.
- NS-3 uses numerous external data analysis, animators, and visualisation tools.
- Users who work in the environment should use the text editor and work with C++ or Python software programing languages.
- Primarily, NS-3 is installed on Linux systems; however, NS-3 can similarly be installed on Windows with the support of FreeBSD and Cygwin.
- Several modules have been developed in NS-3, including the WiMAX module.

In real life, implementation of multicast service virtualization networks would require very expensive hardware equipment items. This is why this research used NS-3 software. NS-3 was chosen because it is an open source and one can write lines of codes for creating virtual instances. Effectively, it implements a multicast service virtualization framework. This work covers a range of fields such as: WiMAX network, network virtualization, and heterogeneous networks. As previously established, NS-3 supports the WiMAX module. Hence, NS-3 was chosen for performance evaluation of multicast service virtualization. In reference [105] and [106], NS-3 was used to allocate network resources and perform the scheduling of nodes and bandwidth management. This is to ensure fairness to achieve improved network performance in terms of throughput, delay, jitter and loss.

NS-3 was used for performance analysis of wireless networks including WiMAX. It delivers video applications through multiple paths and showed that NS-3 can accurately measure the delay at the core and access network in [107], [108] and [109]. Moreover, NS-3 was used to ensure implementation of end-to-end quality of service for video applications in [110], [111] that requires the network to choose the most feasible path in terms of bandwidth, delay and jitter. Research on NS-3 continued to extend physical layer from OFDM to OFDMA in NS-3 WiMAX module [112].

Research in [113] used NS-3 for real-time emulation of LTE network. Additionally, researchers investigated network function virtualization using NS-3 [114] and they managed to perform an efficient resource packet scheduling.

It was possible to carry service migration for LTE network by using NS-3 [115]. The work in [116] implemented the heterogeneous wireless network in NS-3. The use of NS-3 in above studies shows its the accuracy and reliability. The engine of this study implements multicast service virtualization framework using NS-3. The following subsection describes WiMAX features implemented in NS-3.

5.3. NS-3 WiMAX Characteristics

The WiMAX features supported by NS-3 simulator are explained in this subsection; these enable the realisation of this work by implementing the virtualization of multicast service framework in NS-3. The following are WiMAX features implemented in NS-3 as elaborated by work [118], [119]:

- Realistic and scalable physical layer and channel model
- The IP convergence sublayer packet classifier
- Efficient uplink and downlink packet schedulers
- Support of multicast and broadcast services (MBS)
- Packet tracing functionality

Since this thesis is limited to MAC layer and application layer, NS-3 WiMAX MAC model is discussed in the next subsection.

5.4. The NS-3 WiMAX MAC Model

The NS-3 WiMAX MAC model implements three sub-layers: these are the convergence sub-layer, the MAC common part sub-layer, and the security sub-layer. Security is not in the scope of this thesis. Hence, only the convergence sublayer and the MAC common part sublayer are discussed.

The WiMAX model built in NS-3 is formed by C++ classes. At the MAC layer, the WiMAX network device is represented by WimaxNetDevice class. This class can be extended from the NetDevice to the BaseStationNetDevice and SubscriberStationNetDevice classes of the NS-3 API. The API offers the network device abstraction classes by defining MAC layers of BS as BaseStationNetDevice and SS as the SubscriberStationNetDevice. In addition to BaseStationNetDevice and SubscriberStationNetDevice MAC layer classes, the other important functions of MAC are spread over other various classes [118].

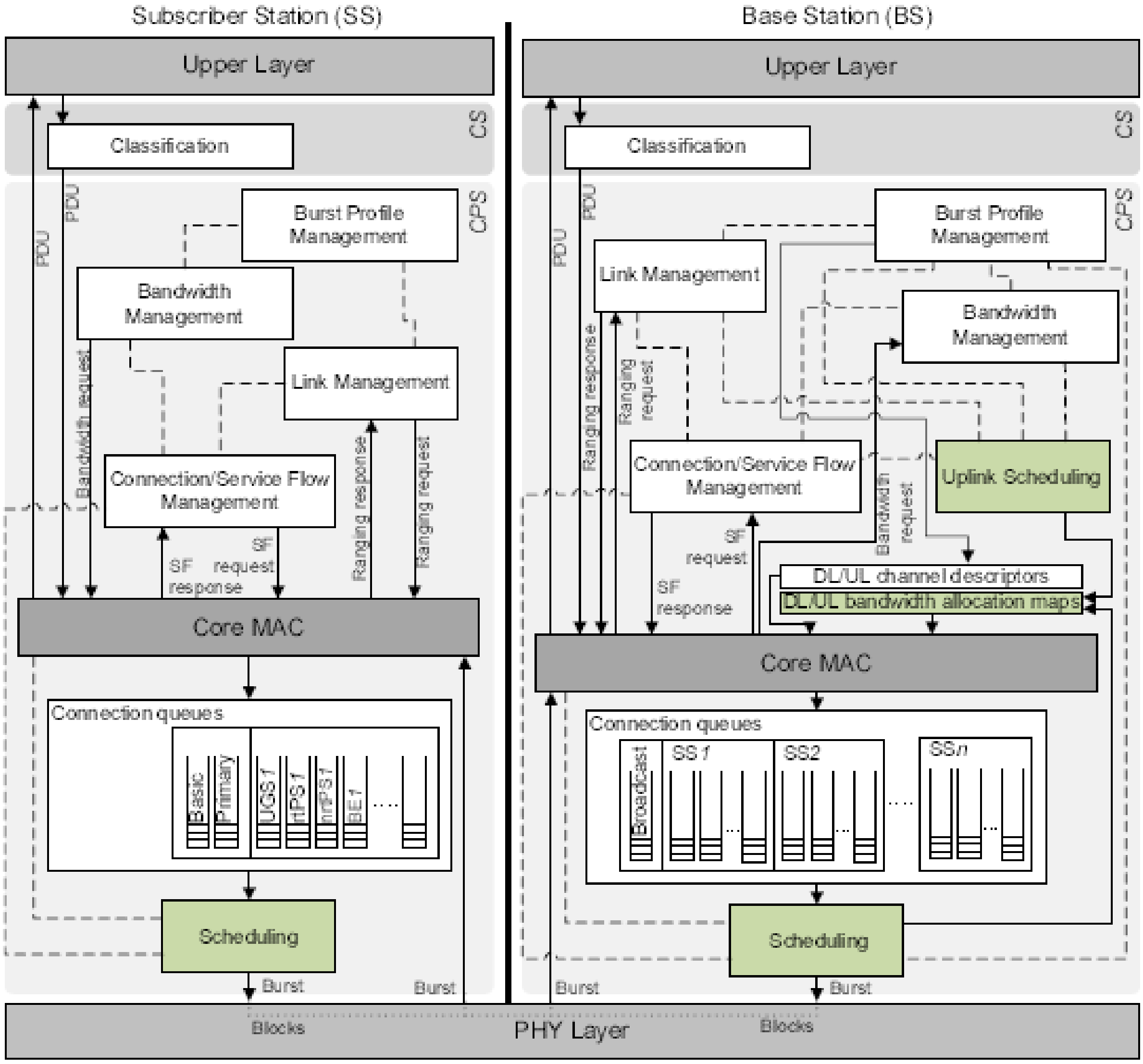


Figure 5.1. Block diagram of WiMAX module in NS-3 [117].

Figure 5.1 describes the functions of the WiMAX MAC layer implemented in NS-3 for both the subscriber station and the base station. The implemented functions are as follows:

- Classification
- Burst profile management
- Bandwidth management
- Link management
- Connection management
- Service flow managemen
- Connection queues
- Scheduling

All the above functions are implemented in subscriber stations and base stations. Additional functions are implemented in the subscriber station. These comprise the uplink scheduling such as DL/UL channel descriptions and DL/UL bandwidth allocation maps. A full description of all C++ classes and the functions implemented for MAC and PHY layer functions in software representation and their interconnection is shown in Appendix A.

5.5. NS-3 WiMAX Outbound Schedulers Model

The outbound schedulers at the base station and subscriber stations side (BSScheduler and SSScheduler) determine the transmission sequence of the packets from the outbound queues in a given allocation of time. At the base station, the scheduler determines the downlink traffic to be transmitted to subscriber stations. Similarly, the subscriber stations schedule the packet to be transmitted to the uplink allocation time that is assigned to that subscriber station. Only multicast services that are downlink services are the concern of this research [104].

5.6. NS-3 WiMAX Support Multicast and Broadcast Services (MBS)

A downlink multicast service, established by the BS, creates a connection with each SS to be associated with the service. Any available multicast traffic with CID value may be used for the service, that is, multicast transport connections do not require dedicated CIDs. The CID used for the service is the same for all the SSs, using the same channel that participates in the connection to ensure a proper multicast operation. It is not required for the SSs to be aware whether the connection is a multicast or broadcast transport connection.

The MAC of each SS receives and processes transmitted data on the connection with a given CID. Consequently, each multicast SDU is transmitted only once. Since a service flow is associated with a multicast transport connection, it is attributed to QoS and the traffic parameters for that service flow [118]. Without MBS features in WiMAX NS-3, it would not be possible to realise the virtualization of multicast service framework using NS-3.

5.7. Multicast service virtualization using NS-3

As it was stated earlier in this chapter, virtualization of the multicast service framework was implemented using NS-3. Based on the hypotheses of this research stated in Chapter 1, the main solution requirement of this experimentation is to enable the interchange of multicast services between users that belong to different virtual networks. Similarly, the delivery of the multicast content through a single virtual network should be activated. The objective of this approach is to achieve efficient bandwidth management whereby a single virtual network is used to deliver multicast content, regardless of the network home of the requesting user. In addition, the expectation from this approach is to improve the network performance. The network performance metrics to be considered are throughput, delay, jitter, and loss. Thus, the assumption stated at the beginning of this study is that each virtual network is a single virtual base station, and that the three users associated with those virtual base stations make a multicast group. Multicast streams flowing from a multicast source are connected to a multicast router by a LAN. Further, the ASNGW is connected to the base station via another LAN. The base stations are connected to mobile stations via air interface. Now, to emulate the virtualization framework in NS-3, multiple virtual networks are established and associated with respective base stations. The virtual base stations are connected to the same access service gateway via different LANs.

The proposed virtual network manager is put in the ASNGW to identify the users from various virtual networks. Similarly, the virtual network manager identifies the content requested by each user and determines the virtual network through which the content should be delivered. This study highlights a WiMAX topology that is emulated in NS-3 to evaluate the performance of a multicast service virtualization framework. Figure 5.2 shows the network topology consisting of a multicast streamer. This provides multicast contents to virtual networks, a local area network (LAN) that connects the multicast streamer to the ASNGW. It also provides N other local area networks that connect the ASNGW to these N base stations respectively. Each virtual network is represented by a WiMAX base station that delivers the multicast content to the multicast groups MG_1 up to MG_N.

Subscriber stations are connected to their respective base stations via wireless media. A number of N subscribers are considered. The subscriber stations can request (and be provided with) the content from any virtual networks. Thus, the traffic patterns are estimated by MILP model and then used in the NS-3 WiMAX module for performance evaluation.

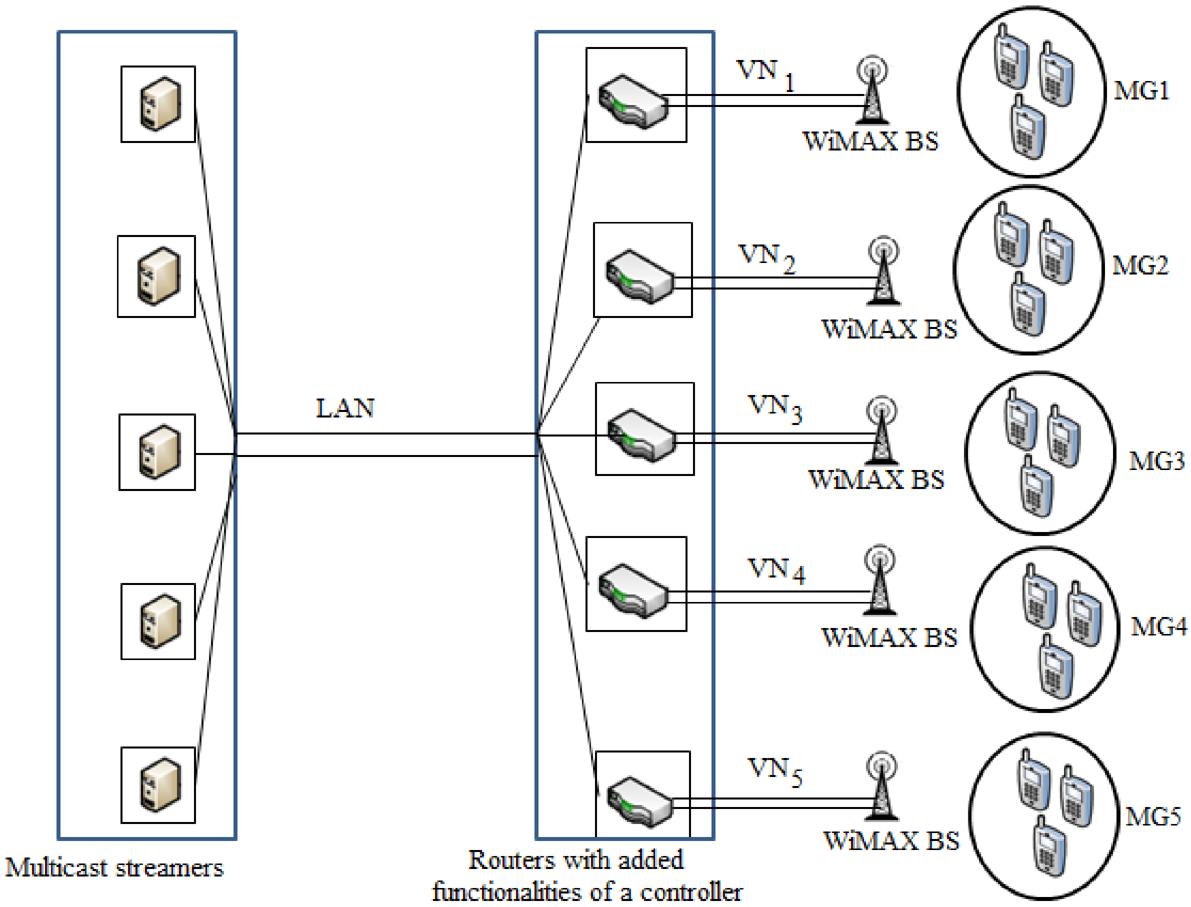


Figure 5.2. Emulation topology for multicast virtualization.

A number of tests are covered to obtain a comprehensive performance evaluation and present their results. A brief software representation of the experimental testbed is illustrated in Figure 5.3. It describes the software representation of multicast services virtualization, where source nodes (MCBCS streamer), destination nodes (SSNodes), the forwarding ASNGW, and virtual base stations of each virtual network are created. From sender nodes, a default multicast route is created to direct the traffic to the interface from which it should be transmitted. Then the traffic arriving at the ASNGW is directed to *ASN_Devs2*.

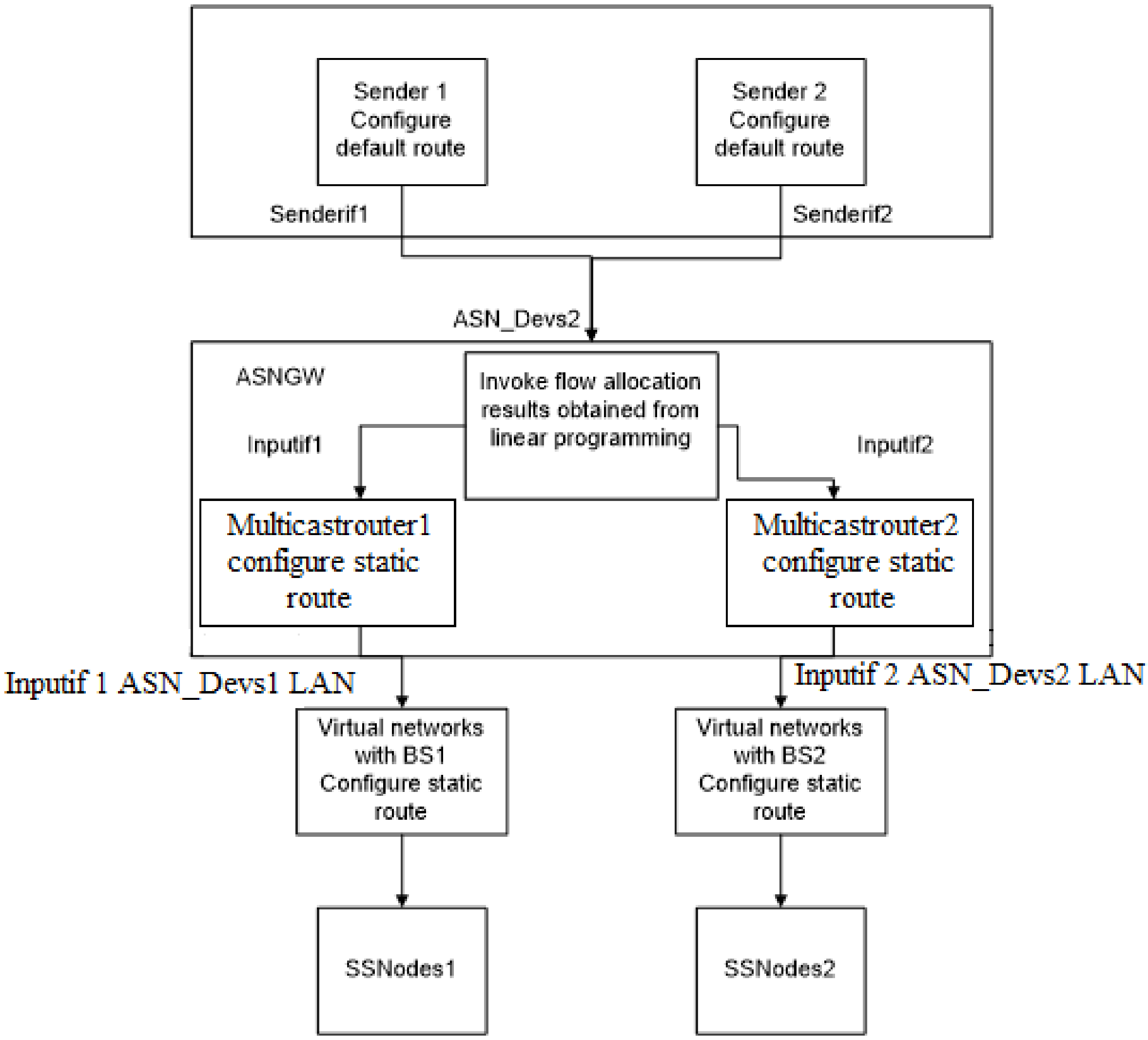


Figure 5.3. Software representation of virtualization of multicast services

The ASNGW invokes flow allocation solution obtained by the MILP that determines which multicast router the traffic should be transmitted to. The static multicast router is configured in the multicast router to direct the packet to the path it would take. This is done by configuring the *Inputif* and *ASN_Devs* through which the packet is transmitted.

Finally, the second static route is configured in each virtual network on the Base Station to determine the path the traffic should take. Appendix B shows the configuration of multicast route in NS-3. In Figure 5.3 above, only two *Inputif* and *ASN_Devs* were considered. However, any number greater than zero can be converted to the number the multicast service virtualization framework can bear. They are then connected to their respective multicast routers, virtual networks and subscriber stations nodes.

5.8. Traffic models

One key issue in simulating a WiMAX network is to know the traffic types and services that the network supports. Thus, finding the correct traffic models to implement in the network simulator is a crucial part of the modelling exercise in order to have a meaningful evaluation. This section describes and explains the traffic model used to evaluate the performance of virtualization of multicast services in WiMAX networks. Four applications as defined in WiMAX application performance guideline in Section 4.7 were considered, namely: VoIP, video streaming, interactive gaming, and media download.

5.8.1. Video Traffic

QoS must be guaranteed in WiMAX networks for the video traffic. The video traffic is modelled using ON/OFF model. The characteristics of the traffic generated are active and silent periods, as shown in Table 5.1 below.

Table 5.1. Video traffic model parameters.

Parameter	**Value**
Packet size	429
Data rate (Mbps)	0.384
Silence period (s)	Constant 0
Talk period (s)	Constant 120

5.8.2. Voice Over IP Model (VoIP)

QoS should be guaranteed in WiMAX networks for the VoIP traffic. The VoIP traffic is generated using an ON/OFF traffic model. The model has active and silent period characteristics as shown in Table 5.2 below. The GSM Enhanced Full Rate (EFR) is the most frequently used encoder for the VoIP traffic model. Appendix C illustrates the generation and characteristics of VoIP application configuration in NS-3.

Table 5.2. VoIP traffic model parameters.

Parameter	Value
Voice Codec	GSM EFR with 12.2 kbps data rate
Packet size	429
Data rate (Mbps)	0.064
Silence period (s)	Constant 0
Talk period (s)	Constant 120

5.8.3. Interactive Browsing

QoS should be guaranteed in WiMAX networks for web browsing traffic. The interactive traffic is generated through an ON/OFF model that models the active and silent time slots as shown in Table 5.3 below.

Table 5.3. Interactive gaming traffic model parameters.

Parameter	Value
Packet size	429
Data rate (Mbps)	0.085
Silence period (s)	Constant 0.04
Talk period (s)	Constant 120

5.8.4. Media Content Download

QoS must be guaranteed in WiMAX networks for media content download traffic. The file download traffic is generated by an ON/OFF model that generates the active and silent continuous time slots as Table 5.4 below shows.

Table 5.4. Media content download traffic model parameters.

Parameter	Value
Packet size	429
Data rate (Mbps)	0.5
Silence period (s)	Constant 0
Talk period (s)	Constant 120

The next section reports the simulation scenarios that were set up, the performance measures and final results obtained. The ability of MILP to allocate flows in multicast services virtualization framework is evaluated by means of VoIP traffic, interactive gaming traffic and media content download traffic over virtualized Mobile WiMAX. The simulation results explore how the developed allocation model of multicast flows to virtual networks provides better performance. The performance metrics used in these scenarios are throughput, average delay and jitter, and actual packet loss.

5.9. Performance Measures

The metrics computed for the performance evaluation in this thesis are briefly described in this section. The code lines were written to compute these performance metrics and the flow monitor helper captured the average jitter, throughput, average delay, and packet loss measurements as shown in Appendices D and E.

5.9.1. Throughput

Throughput is the total amount of data that a subscriber station receives from the sender in a determined interval of time.

$$Throughput = \frac{Total\ amount\ of\ data\ received}{Time\ last\ packet\ was\ received - Time\ first\ packet\ was\ transmitted}$$

5.9.2. Delay

Delay is the amount of time a packet takes throughout the transmission in a network from source to destination. The delay is computed by considering the difference between the packet transmission time and reception time.

$$Delay = The\ current\ time\ the\ packet\ is\ received - The\ current\ time\ the\ packet\ is\ sent$$

5.9.3. Jitter

Jitter is the difference between the two successive time delays. The formula to calculate the jitter is expressed by

$$Jitter = Delay\ of\ current\ packet - Delay\ of\ previous\ packet$$

5.9.4. Packet loss

Packet loss is the difference between the transmitted number of packets less the number of received packets, and divided by the number of transmitted packets. This is expressed in percentage and is given by

$$Packet\ loss = \frac{The\ number\ of\ transmitted\ packets - The\ number\ of\ received\ packets}{The\ number\ of\ transmitted\ packets}$$

5.10. Experimental Setup

This section reveals results obtained from NS-3 simulations that were conducted with the objective of testing the ideas developed in this thesis. The results are discussed and properly explain the performance of the proposed model that allocates multicast flows in multicast services virtualization framework and improves the network performance.

Thus, experiment results are based on the validation of the use of MILP for delivering multicast flows through a single virtual network network as stated by this thesis theory. Similarly, the experiment results focus on network performance testing when applying the optimal allocation of multicast flows to virtual networks for bandwidth efficiency. This confirms the mathematical model related to throughput optimisation.

The network performance is measured on the basis of the following metrics such as throughput, delay, jitter, and packet loss when flows are sent over a single virtual network. In this way, the performance is evaluated in relation to the selected virtual networks. The objective of this work is to transmit a flow over a single virtual network to a multicast group that uses bandwidth efficiently and improves the network performance. Still, depending on virtual network capacities, multicast flow rates, number of multicast flows and virtual networks, the network performance displays various behaviours.

On the other hand, this chapter presents the evaluation results of MILP as generalized assignment problems. This helps determine the decision of multicast flow transmission on multiple virtual networks. Initially, the terms that are involved in the GAP problems are estimated. Thus the throughput was computed based on Equation (4.6). For the throughput computation, the work considered three and five multicast flows respectively. The experiment was based on the increase in the number of flows and virtual networks in which similar results were found. For this reason, only the results of the three flows experiments are presented because there was no change in the results when the number of flows and virtual networks were changed. However, from the results of the experiments, it was observed that all offer better network performance and improve bandwidth use when MILP is applied. In case of three flows, VoIP, streaming media (video clips), and media content downloads were considered, while for five flows, interactive gaming, VoIP, streaming media (music and video clips) and media content downloads were considered. Thus, virtual network bandwidth capacities used in this work are arbitrarily chosen. However, this is in the range of acceptable Carrier Sense Multiple Access (CSMA) link capacities. Consequently, the network capacities chosen for three and five virtual networks are 10, 5, 2 Mbps and 10, 5, 4, 2, 7 Mbps respectively.

5.11. Validation of Throughput Estimation

The flow allocation model formulated in Chapter 4 consists of different parameters that need to be calculated in order to get a solution. It is in this regard that Equation (4.6) was developed to determine the throughput to be used for solving the flow allocation problem.

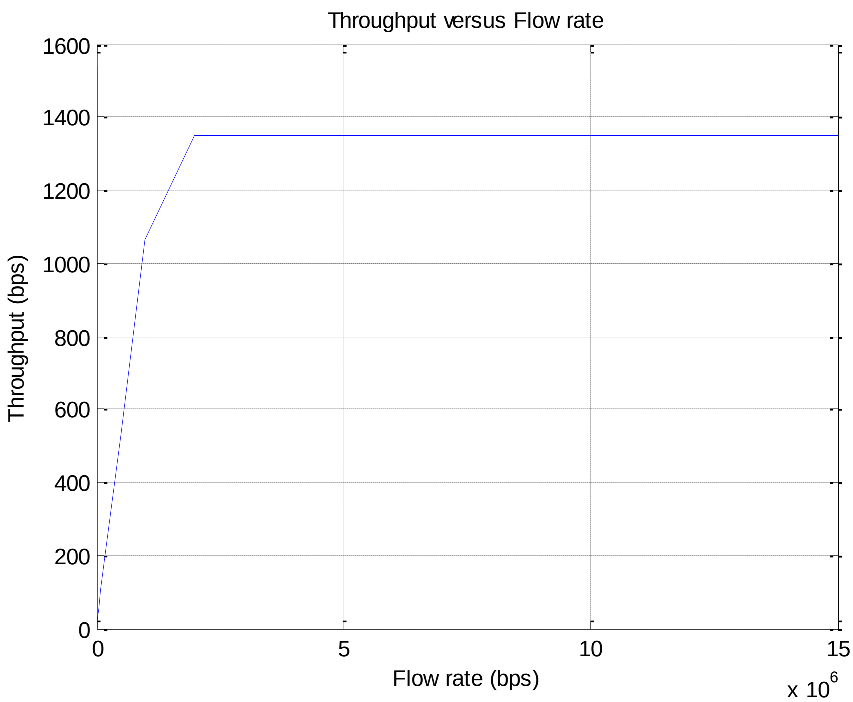


Figure 5.4. Throughput versus flow rate estimation.

The parameters set in Equation (4.6) fed the NS-3 simulator to validate the developed equation. Figure 5.4 shows the throughput estimation graph that confirms the throughput obtained by Equation (4.6) proposed in the Chapter 4. This was proven by considering the following values for flow data rate, in the case of fixed network capacity and the same type of traffic. The following data rates in kbps were used: 0.15, 0.20, 0.5, 1, 2, 3, 4, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000, 10200, 10500, 11000, 12000 and 15000. Thus, the throughput has been computed for each value, and this gives the logarithmic graph as it is shown in Figure 4.8 (see Chapter 4).

5.12. Validation of Research Hypotheses

The objective of this thesis is to enable users from multiple networks to share the content between them and to utilise the bandwidth efficiently. This can only work when the same multicast content is delivered to all multiple networks users. Likewise, it is delivered through a single network rather than through multiple virtual networks. It thus improves the network performance and efficient use of bandwidth which are the main concerns of network providers. In order to achieve this, the GAP was formulated and MILP was used to solve the flow allocation issues. Thus, the evaluation results of this study are highlighted in Chapter 4. Obviously, MATLAB results are fed to NS-3 to evaluate the performance of MILP for flow allocation problems. Nevertheless, intensive simulation and then multiple cases were considered. As a result, the case of three flows and three virtual networks was chosen to be presented, since all of them gave the same results in terms of the evaluation of using MILP approach as stated in Section 5.10. Throughputs, delays, jitter, and losses on the same virtual network were compared within themselves when MILP was not used and when used.

5.12.1 Simulation Scenarios and Results

Table 5.5 describes parameters used in case of three virtual networks and three flows. It was assumed that there are three users, and each belong to three multicast groups. The first multicast group is for users that request VoIP content. The second is for users who request streaming media content, and the third is for users who request media download content. Initially (since each user is supposed to receive all three contents), for any user to receive the three contents, the content should be delivered through the three virtual networks. With the developed virtualization framework in this thesis, after using MILP for the allocation of flows to the virtual networks, it is obvious that instead of delivering multicast flows through multiple virtual networks, the content should be delivered to the selected virtual networks. This leads to efficient use of bandwidth and better network performance. The work results compare the throughput, delay, jitter, and losses with and without MILP to allocate flows to virtual networks.

Table 5.5. Parameter chosen for the first scenario

Parameter	**Configurations**
Total number of virtual networks	3 virtual networks
Total number of multicast flows on a virtual network	3 multicast flows such as VoIP, Video streaming, media download
Number of multicast users in each virtual network requesting video content	3 users from each virtual network
Channel model	(implemented in NS-3)
Frequency of operation	10MHz
Traffic models	Described in Section 5.8
Simulation run time	100 seconds
MAC scheduler	WimaxHelper::SCHED_TYPE_SIMPLE

Three flows and three virtual networks

For the scenario of three flows and three virtual networks, the following network capacities were used: 2 Mbps, 10 Mbps, and 5 Mbps for VN1, VN2, and VN3 respectively. The three flows rate was set to 64 Kbps, 384 Kbps, and 500 Mbps for their respective applications. These are VoIP, streaming media, and media content download. Each virtual network has one user and each user belongs to three multicast groups that request the three mentioned flows.

In addition, VoIP and streaming media flows were selected to be delivered to VN2 and media download was selected to be delivered to VN3. Surprisingly, none of the flows was allocated to VN1. The above settings were applied to all evaluation metrics such as throughput, delay, jitter, and loss. This work has focused on the improvement of efficient use of bandwidth and network performance. This is managed through multicast traffic delivery via a single virtual network instead of delivery through multiple virtual networks based on MILP. Thus, evaluation of the proposed approach considers the run of experiments using MILP on one hand and, on the other, without MILP. The network performs well when based on MILP.

Throughput comparison

In evaluating the network performance in terms of throughput in three different virtual networks using the NS-3 simulation, it was observed that the throughput achieved on VN2 and VN3, with the use of MILP, is above the throughput achieved in the other case as shown in Figure 5.5.

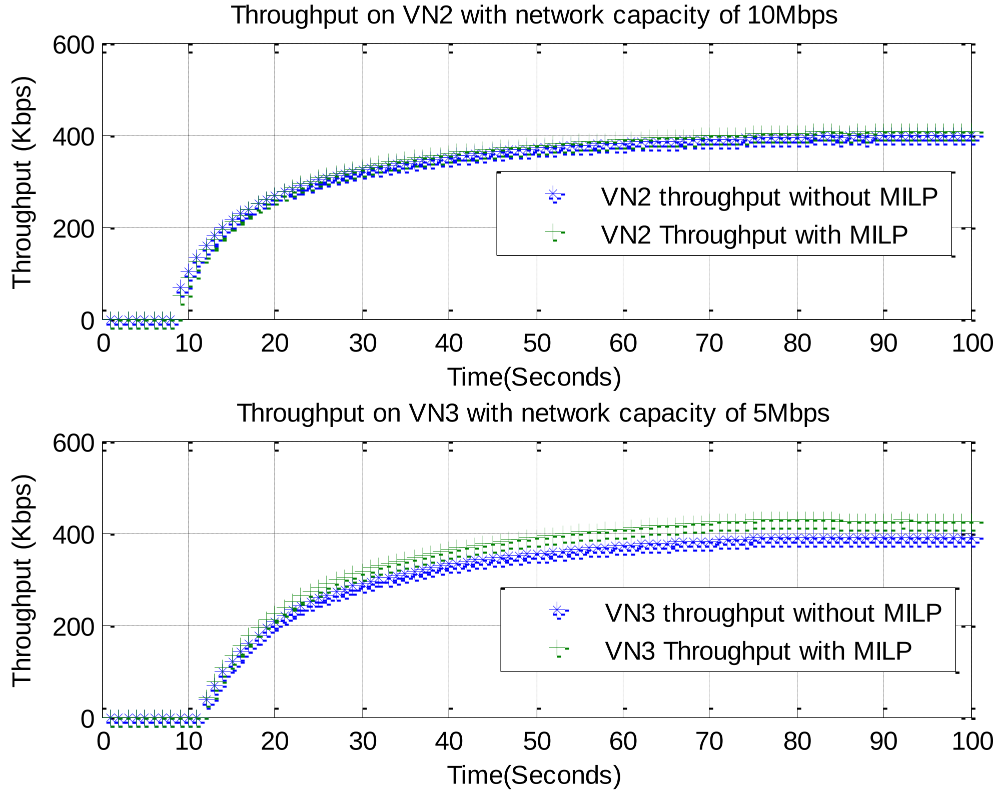


Figure 5.5. Throughput on VN2 and VN3.

Table 5.6 clearly explains virtual network capacity flow rate used without MILP. This is the flow rate of all three users, throughput achieved without MILP, flow rate used with MILP after selection of the network, and throughput achieved with MILP. Thus, results show that the throughput is almost the same in all cases. However, if the flow rate and throughput in both cases are looked at with the use of MILP, the performance is better without MILP since in the latter case the networks are overloaded.

Table 5.6. Flow rate and virtual network capacities versus throughput.

Virtual networks	**Virtual network capacity**	**Flow rate without MILP**	**Throughput without MILP (Kbps)**	**Flow rate with MILP**	**Throughput with MILP (Kbps)**
VN2	10 Mbps	948 Kbps	396 Kbps	448 Kbps (VoIP + Streaming media)	406Kbps
VN3	5Mbps	948Kbps	390 Kbps	500 Kbps (Media content download)	425.8 Kbps

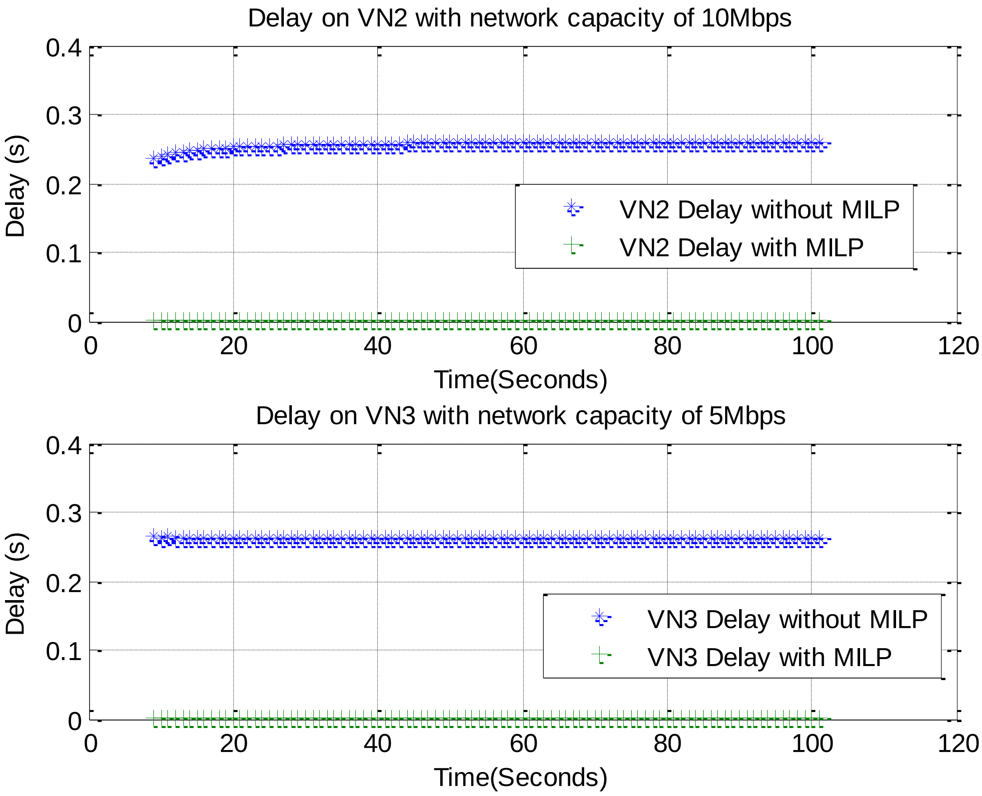


Figure 5.6 Delay on VN2 and VN3.

Delay comparison

From the evaluation done on the three virtual networks for delay metric, it was observed that the delay on the two virtual networks, with the use of MILP, is almost zero compared to the delay in the case where MILP is not used, as shown in Figure 5.6. Obviously, it is an indication of better performance of MILP. Table 5.7 shows the delay each virtual network experienced, with and without MILP respectively. With the use of MILP the minimum delay is observed.

Table 5.7. Flow rate and virtual network capacities versus delay

Virtual networks	**Virtual network capacity**	**Flow rate without MILP**	**Delay without MILP (s)**	**Flow rate with MILP**	**Delay with MILP (microseconds)**
VN2	10Mbps	948Kbps	0.26	448Kbps (VoIP + Streaming media)	2.697
VN3	5Mbps	948Kbps	0.262	500Kbps (Media content download)	2.681

Jitter comparison

In this case, jitter metric is considered. The evaluation from the experiment results reveals that there is a decrease of jitter values when MILP is used and an increase of jitter when MILP is not used, as shown in Figure 5.7. The jitter values obtained on each virtual network is low when MILP is used as shown in Table 5.8. Hence, the better network performance is achieved when MILP is used.

Figure 5.7 Jitter on VN2 and VN3.

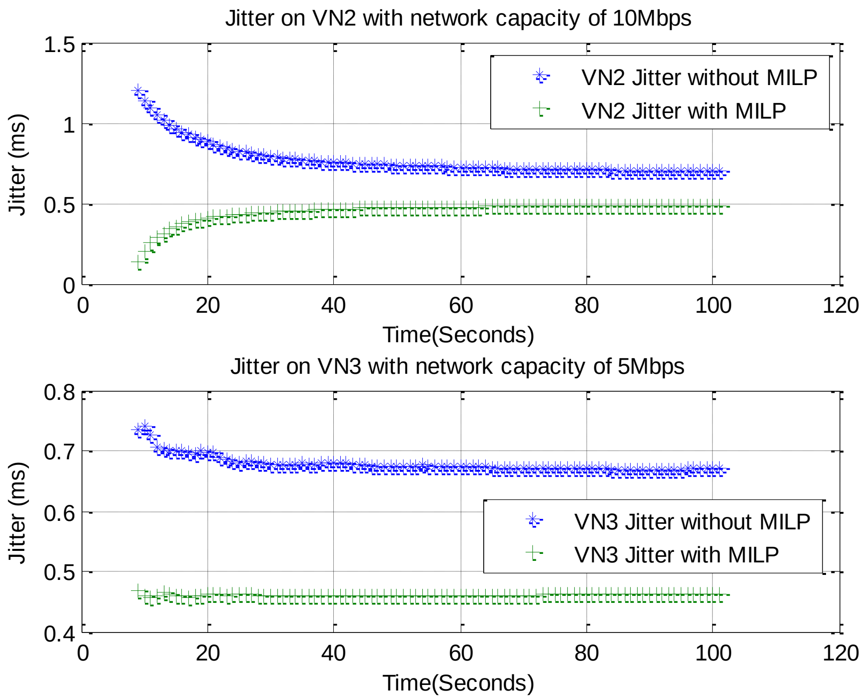


Table 5.8. Flow rate and virtual network capacities versus jitter

Virtual networks	Virtual network capacity	Flow rate without MILP	Jitter without MILP (ms)	Flow rate with MILP	Jitter with MILP (ms)
VN2	10 Mbps	948 Kbps	0.697	448 Kbps (VoIP + Streaming media)	0.48
VN3	5 Mbps	948 Kbps	0.67	500 Kbps (Media content download)	0.46

Table 5.9. Flow rate and virtual network capacities versus loss

Virtual networks	Virtual network capacity	Flow rate without MILP	Loss without MILP (%)	Flow rate with MILP	Loss with MILP (%)
VN2	10 Mbps	948 Kbps	0.52	448 Kbps (VoIP + Streaming media)	0
VN3	5 Mbps	948 Kbps	0.52	500 Kbps (Media content download)	0

Loss comparison

The three virtual networks were evaluated for loss metric. It was observed that the loss on two virtual networks with the use of MILP is almost zero compared to the loss when MILP is not used. This is shown in Figure 5.8 and is an indication of better performance of MILP. Table 5.9 shows the loss each virtual network experienced with and without MILP respectively. With the use of MILP, however, the minimum losses are observed. Therefore, the minimum losses with the use of MILP are due to low flow rate that is sent over the network by the delivery of multicast traffic through a single virtual network. This is done instead of the delivery through multiple virtual networks.

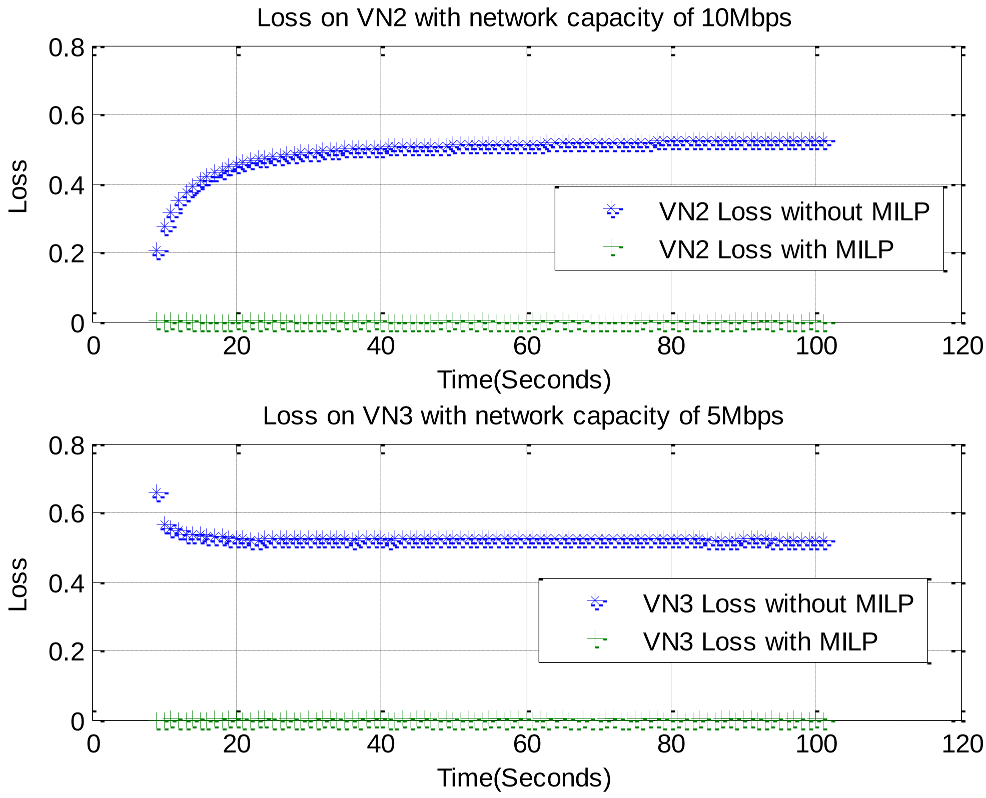


Figure 5.8 Jitter on VN2 and VN3.

5.12.2 Static and dynamic virtual network capacities with the use of MILP

Throughput for static virtual network

As it was discussed in chapter 4, the flows were allocated to virtual networks where two scenarios were considered: static virtual network and dynamic virtual network capacities. Observation revealed that in the static virtual network capacities, the flow allocation is always static. While in dynamic virtual network capacities, the flows allocation are different in different experiments. In this case, virtual VN2 is configured to have the network capacity of 10 Mbps for the two simulations, and the flows rates are different from the throughput on VN2. This remains static in both two cases as shown in Figure 5.9.

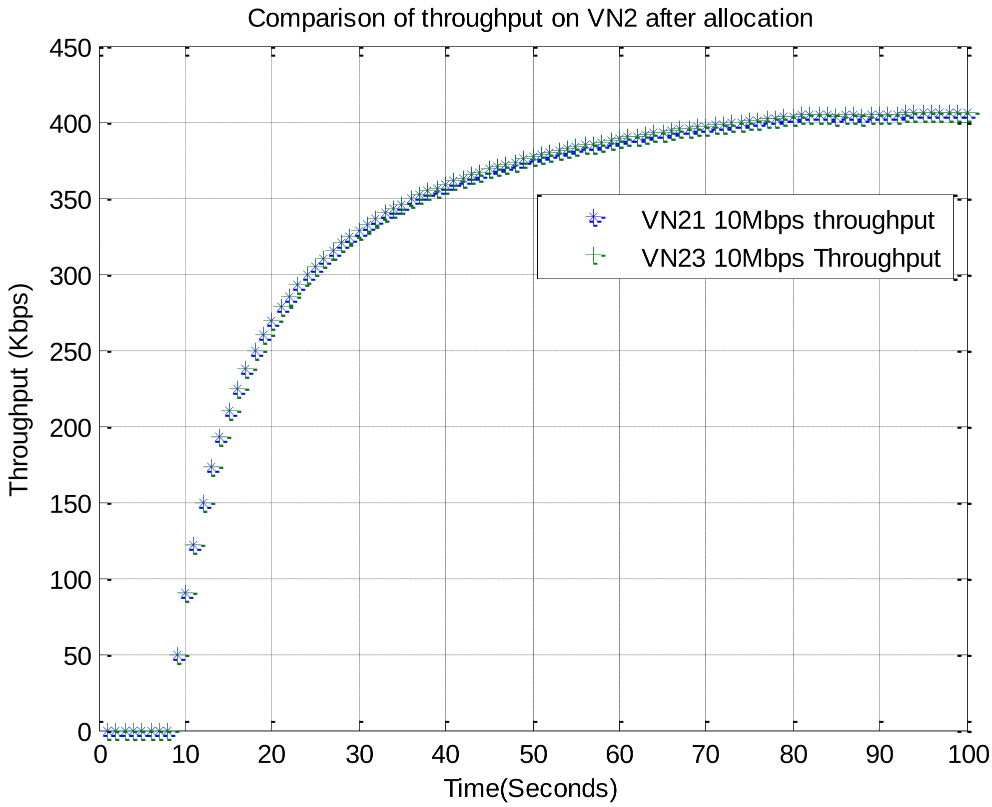


Figure 5.9. Comparison of throughput on VN21, VN23=10 Mbps with MILP

Throughput for dynamic virtual network

In order to study the impact of change in the virtual network capacity on the network performance, VN1 was considered. VN1 was assigned 10 Mbps and 5 Mbps and the throughput was measured respectively. The results in Figure 5.10 show that once the network capacities change, the network throughput also varies; hence the network capacity with higher flow rate achieves higher throughput.

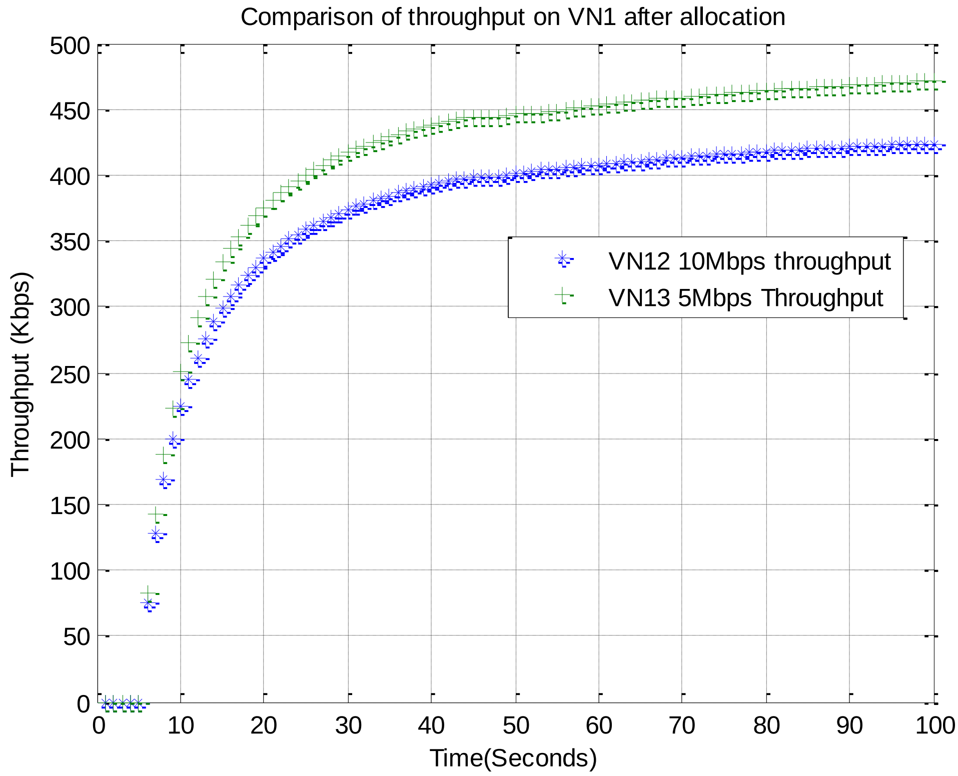


Figure 5.10. Comparison of throughput on VN12=10 Mbps, VN13=5 Mbps with MILP

5.18. Summary

This chapter described the fundamental module of WiMAX and features of WiMAX that are implemented in NS-3. Similarly, it has analysed the solution of multicast traffic allocation to virtual networks, and described multicast service virtualization in NS-3. Traffic models used in this research are explained, namely, VoIP traffic and video traffic, web browsing and file download. The performance metrics for hypotheses evaluation have been explained.

In this chapter, the network scenario implementation is explained, namely: video trace files properties used in simulation and VoIP application, as revealed by this work. The performance measurement and how it is computed is explained. The following performance metrics were considered: throughput, delay, jitters, and packet loss. The chapter equally explains the implementation scenario. The simulation consisted of virtual networks, multicast streamer, local area networks, access service network gateway, virtual base stations, and subscriber stations. A multicast service, the focus of this thesis, is provided over these virtual networks.

A setup scenario was implemented in NS-3 where a virtual network was created and multicast flows were generated. According to results from linear programming of this chapter, transmission of multicast flows in NS-3 to their respective virtual networks is reviewed. This is based on the allocation obtained from the current chapter. The characteristics of transmitted multicast flows are the drum beat of the chapter. Three types of traffic were considered in the NS-3 implementation: VoIP, video streaming, and media content download traffic. The performance criteria for evaluating the hypotheses are found in this chapter.

CHAPTER 6

6 CONCLUSIONS AND RECOMMENDATIONS

6.1. Review of Essential Results

This research report has reached its conclusion. It was based on the following hypotheses: a virtualized multicast service framework can efficiently manage bandwidth resources by providing better network throughput with reduced delay and jitter by optimum allocations of flows to virtual networks. It also provides better QoS to users with the use of multicast scheduling as stated in the introduction chapter. The objective was to enable the interchange of multicast services among different users by using multicast services virtualization. Literature in this study reveals that wireless networks have bandwidth problems. This thesis has tried to solve these bandwidth problems. From results obtained in the previous chapter, virtualization of multicast services and a developed allocation scheme of multicast flows to virtual networks offer better performance and improve the efficient use of bandwidth. This is guaranteed with the improved throughput and reduced average delay, jitter, and packet loss.

6.1. Summary and conclusions

The thesis begins with some background information on virtualization and multicasting services over WiMAX networks, as covered in Chapter 1. This subsection describes the contributions of this research.

Chapter 1 highlighted the focus of this research on how virtualization of multicast services can enable efficient utilisation of bandwidth in WiMAX networks. Instead of sending multicast content to users from and via multiple virtual networks with the help of virtualization, the same content can be sent via a single virtual network which leads to better network performance. Some of the multicast services that can be offered to subscribers include interactive gaming, VoIP, streaming media, and media content download. Similarly, Chapter 1 informed on the research motivation that virtualization of multicast services enables users to have flexibility and scalability of access to applications and data. The research hypothesis is also introduced, based on the observation that the current multicast service provision over WiMAX networks consumes too much bandwidth. They equally limit access to multicast services from other virtual network. Virtualization is necessary to provide multicast services over WiMAX networks to enable the cooperation of different virtual networks for improved network performance.

Chapter 2 started with the background related to WiMAX and multicasting. This chapter defined and explained the WiMAX technology in detail. It showed its importance in relation to other wireless access technologies. Chapter 2 presented a review of multicasting services concepts. This thesis focused on multicasting services related to scheduling and showed a full definition of the research problem. It concluded with a definition of multicasting, and the importance of multicasting in network. Similarly, it showed how multicasting is important, and that different multicasting layers exist. In essence, the research problem was the limitation of bandwidth in wireless network and network efficiency in the present WiMAX network. This was due to high bandwidth demand of multicast services, and the increase in the number of subscribers that request multicast services.

Chapter 3 defined virtualization and the importance of virtualization in all domains. This was written to give a full understanding of the theory that is used throughout the thesis. Chapter 3 started with a review of the related works on virtualization. The review on network virtualization analysed the current studies on wired network virtualization. The chapter reviewed wireless network virtualization and different wireless access technologies, including WiMAX, LTE, WiFi, and the like. This showed that virtualization is categorised into three clusters such as: spectrum level, flow level, and network level virtualization.

The formulation of the solution to the research problem started in Chapter 4. It began with the formulation of the model according to the nature of problems. The model was formulated by using the Generalized Assignment Problem (GAP), which was transformed to knapsack problems, in order to allocate the multicast traffic to different virtual networks and found the optimum efficiency for the network. Chapter 4 revealed a proposed mechanism for allocating multicast flows to virtual networks. This mechanism was based on the Mixed Integer Linear Programing method. The chapter presented and discussed the allocation of multicast flows to the virtual network and their results. Chapter 4 implemented and solved the developed model by Mixed Integer Linear Programing to determine the allocation of multicast flows to virtual networks. The chapter presented the experimental testing of ideas that were analyzed through MATLAB. It finally reported the performance evaluation and results discussion.

Chapter 5 covered the research methodology and designed the WiMAX model in NS-3. The experimental testing of developed ideas was conducted by using NS-3. Chapter 5 evaluated the performance of the allocation from the previous chapter, and the results revealed an improved performance. The simulation made use of features provided by WiMAX model in NS-3, such as OFDMA channel, scheduling types, QoS classes, and existing applications. In addition, the simulation used multicast streamer, local area networks, virtual base stations, access service network gateways and subscriber stations that were randomly, chosen as the base stations are virtual instances of virtual base stations located in the same place. Finally, chapter 5 revealed the results of simulations conducted in this research. The validation results of the research hypotheses tests were presented first. The results have revealed a better performance of the proposed model. Obviously, the results improved the multicast WiMAX example already implemented in NS-3. These results indicated that virtualization of the multicast services, while transmitted on a single virtual network (rather than on multiple virtual networks), offers optimum bandwidth with reduced average delay, jitter, and actual packet loss.

6.2. Research Contributions

This thesis has a number of contributions. The first contribution is that it has designed a virtualized multicast services framework over a WiMAX network. This accommodates multiple virtual network operators. The network operators provide multicast services to their subscribers with different QoS services, depending on which multicast traffic is to be delivered through that virtual network. The virtualized multicast services framework is not limited to WiMAX only. It can be extended to other wireless access technologies, including LTE, UMTS and others.

The second contribution is the novel design of using Mixed Integer Linear Programing for allocating multicast flows to a particular virtual network. A new model for estimating flow throughput in virtual networks was proposed. This design has the capability of optimising the efficiency of virtualization of multicast services framework. It takes into account QoS demands of each multicast flow. The comprehensive literature review of this thesis has revealed that all such research in the field of multicasting flow was done in heterogeneous network to improve performance by allocating the multicast traffic over more than one access network. Similarly, this current research project developped an equation to compute the throughput with an algorithm that selects the virtual network to which the multicast traffic should be transmitted.

Other studies also used overlay to map multicast nodes to physical networks. The use of a virtual network to transmit multicast content over virtualized WiMAX network is, therefore, an original contribution. This is an innovation in designing a virtual network selection. It designs a resource allocation scheme of virtualized WiMAX networks that accounts for the possibility of using a single virtual network selection method for multicast traffic, to enhance performance and efficiently use bandwidth. The simulation results have revealed that sending the multicast traffic to a single virtual network efficiently improves bandwidth use and provides higher network performance.

A third contribution is a new scheduling algorithm introduced at virtual base station level. The designed scheduling algorithm determines the transmission rate of multicast traffic based on QoS. This selects the multicast group to transmit first on the basis of the multicast traffic aggregated throughput. The results reveal the network performance improvement. Thus, this thesis has developed a new equation to compute multicast flow rate based on the computed rate. Therefore, the multicast group was scheduled to transmit the rate at a certain time.

6.3. Conclusions on research objectives

How can the virtualized multicast service framework achieve efficient network resource utilisation? This thesis focused on efficient bandwidth utilisation with a special estimation for multicast service in WiMAX networks. This objective was achieved through virtualization of multicast services which enables multiple networks to run on the same physical infrastructure. Thus, it offers flexibility to networks to add programmable entity in WiMAX networks. Those networks can use the model developed in this thesis and solution to determine which virtual networks the multicast content will be delivered to, regardless of the network the user is subscribed to. The developed framework is proven to achieve efficient bandwidth application and better network performance while a single virtual network can be used to deliver similar multicast traffic.

The virtualized multicast service framework enables interchange of service delivery on a shareable network infrastructure through virtualization. This allows the network providers to share infrastructure and, from the previously mentioned objective of this research, whenever a user asks to join a multicast group the additional entity will immediately know to which network the user belongs. Thus, it will directly add the user to the multicast group because it has the identification of that user. Also whenever the content is available to that group the added unity, which is the virtual network manager, will deliver the content through the selected network. This was implemented by means of NS-3 simulator that enables a virtualized multicast service framework to interchange service delivery among many networks on a shareable network infrastructure. The investigation revealed that sharing the infrastructure of WiMAX networks, through network virtualization technology integrated with multicast services, leads to an interchangeable service between network operators or providers.

How can multicast traffic be efficiently allocated to a virtualized multicast service framework and network performance optimisation? Review of the related works in this thesis focused on efficient allocation of multicast flows and network performance optimisation. Special focus on multicast service virtualization in WiMAX networks was highlighted. The works introduced a futuristic perspective of multicast flow allocation, through GAP and MILP in MATLAB, to solve the flow allocation problem. A virtual network was selected so that multicast flow should be delivered to the best network which offers optimum throughput. The results of this thesis reveal that flows are delivered from the selection of a virtual network. Thus, the overall throughput always remains the same. However, based on the selected virtual networks, the throughput on individual virtual network is different. Similarly, this thesis has shown that whenever virtual networks capacities are kept fixed (that is, static network capacity) and the flow rates are varied, the allocation remains unchanged. On the other hand, if the virtual network capacities are changed, that is, dynamic network capacity, the allocation changes. To avoid overloading it is better to always keep the same virtual network with the multicast traffic. This way the virtual network capacity becomes dynamic. However, more investigation is still needed in the area of network capacity.

After conducting experiments in MATLAB, three virtual networks were chosen to evaluate the network performance. Three flows were given attention. This was brought to NS-3 simulator for the proposed framework. Here the thesis involved the implementation and validation of a comprehensive virtualization of multicast services in WiMAX simulation model according to WiMAX forum and IEEE 802.16. Thus, the corresponding WiMAX subscriber stations, base stations, with their respective protocols have been modelled and implemented. The NS-3 WiMAX module is used for scientific research and development for students' theses [117], [118]. Consequently, flow monitor was used to collect results and the metrics which have been measured were: throughput, delay, jitter and loss in order to evaluate the performance. The results proved that the proposed solution offers better performance for all metrics. The reduction in delay, jitter and loss is higher than when the solution, as proposed by this thesis, is not applied accordingly. In fact the developed algorithm achieves optimised allocation of multicast traffic in the virtualized multicast service framework.

Therefore the designed algorithm that selects the optimum multicast rate and scheduling of multicast traffic in virtual network is efficient. Additionally, the rate selection that considers delay constraints for better network performance improvement is useful. The performance of different multicast content schedulers on the end user performance and optimum rate selection were investigated and analyzed by means of both simulations and analytical tools. The simulation results revealed that the optimized multicast content scheduler and rate selection offers better QoS to users. This simulation provides optimized network performance and good QoS guarantees to users. Moreover, the scheduler is very simple, it is easy to implement, and only requires small computations. All these operations make the scheduler a very practical solution for real product deployments. Thus, the objectives of this research have been reached because the designed multicast service virtualization framework achieves better performance and uses bandwidth efficiently. Finally, it can be successfully tested and practically applied in the future.

6.4. Research Limitations

The experimental part of this research is based on a number of assumptions. These take the form of numerical values of parameters that were used in the simulations. Examples of the numerical values that were chosen almost arbitrarily are the number of virtual networks, where three and five virtual networks were used. Additionally, the number of virtual base stations and the number of subscriber stations is one in each virtual network. In this thesis, the number of subscriber stations was not considered in the allocation of multicast flows. On the contrary, with these arbitrarily chosen values, the simulations were applied in both cases and had the same results for a better network performance with the proposed virtual network selection methods. But not all the numerical values were chosen arbitrarily.

For example, flow rate settings of VoIP, streaming media, and media content download multicast flows were imposed on the simulations by the values defined in chapter 4. Another example is the choice of network capacity which is for CSMA links and, according to chapter 4, the values are chosen from 1 to 10 Mbps. In the case of this thesis, the values chosen are mentioned in chapter 4 and 5 for scenario setup.

Other parameters, such as the mobility of subscriber stations, were not considered. This was because in multicast virtualization the base stations were positioned in one place. This implies that the distance between a user and a base station is the same as the distance between the same user and all other base stations. Thus, the mobility model of subscriber stations implemented in NS-3 was not exploited. The thesis did not also consider the issue of content request and content retrieval from the server's side. This may constitute another theme for future studies. Note that even though the numerical settings were mainly chosen arbitrarily, as more than one of those numerical values were used, they were able to fulfil the objectives of this research. No specific concerns were pursued regarding the multicast trees, and the content distribution mechanisms were not addressed. The content is provided at the NSP's side. The above stated reasons are considered as the limitations of this research, and thus future investigation is required.

6.5. Recommendations for Future Research

This study mentioned four areas that require further investigation on using multicast media. These are:

- Investigation on QoS persistency in multicast virtualization
- Virtualization hierarchy
- Scalability of users' services
- Extension of the base station in virtual networks

Investigate QoS persistency in multicast virtualization: In this thesis, the persistency of QoS was not considered because each virtual network would implement its dynamic QoS according to different network behaviours. The research recommends this area for future study.

Virtualization hierarchy: In this thesis, a flat network virtualization was considered. However, the work did not have multiple virtual levels above others to investigate how many levels network virtualization can bear. The recommendation for future work is to investigate virtualization hierarchy in order to determine the number of virtual levels that multicast virtualization can support.

Scalability user's services: This thesis did not consider the effect of the number of users in a multicast group on flow allocation. The research should investigate further to find out the impact of users on the allocation of flow.

Extension of base station in virtual networks: The research also considered one base station in each virtual network. The recommendation for future work is to extend from one base station to multiple base stations in each virtual network to involve MBS zones in MCBCS.

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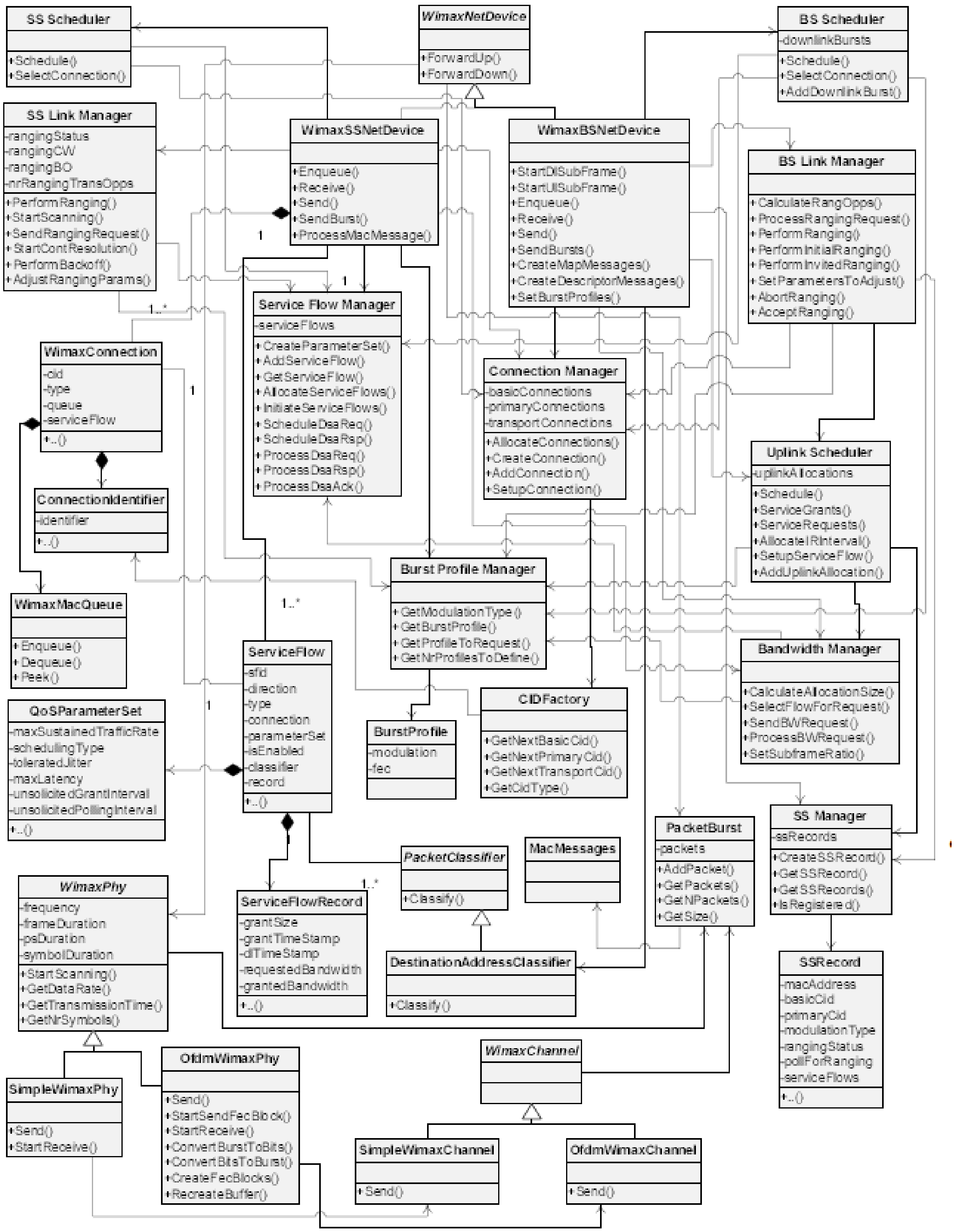
APPENDICES

Appendix A: Proposed WiMAX model class diagram [117].



Appendix B. Configuration of multicast route of virtual networks in NS-3.

```
// Static route of virtual network 1
Ipv4StaticRoutingHelper multicast1, multicast2, multicast3;

// 1) Configure a (static) multicast route on ASNGW (multicastRouter)
Ptr<Node> multicastRouter1 = ASNGW_Node.Get (0); // The node in question
Ptr<NetDevice> inputIf1 = ASN_Devs2.Get (0); // The input NetDevice
multicast1.AddMulticastRoute (multicastRouter1, multicastSource1, multicastGroup1, inputIf1, ASN_Devs1);

//Static route of virtual network2
// 1) Configure a (static) multicast route on ASNGW (multicastRouter)
Ptr<Node> multicastRouter2 = ASNGW_Node.Get (0); // The node in question
Ptr<NetDevice> inputIf2 = ASN_Devs2.Get (0); // The input NetDevice
multicast2.AddMulticastRoute (multicastRouter2, multicastSource2, multicastGroup2, inputIf2, ASN_Devs3);

//Static route of virtual network3
// 1) Configure a (static) multicast route on ASNGW (multicastRouter)
Ptr<Node> multicastRouter3 = ASNGW_Node.Get (0); // The node in question
Ptr<NetDevice> inputIf3 = ASN_Devs2.Get (0); // The input NetDevice
multicast3.AddMulticastRoute (multicastRouter3, multicastSource3, multicastGroup3, inputIf3, ASN_Devs4);
```

Appendix C: VoIP characteristics and generation in NS-3.

```
//Configure the VoIP application
OnOffHelper onoffhelper1 ("ns3::UdpSocketFactory",
                    Address (InetSocketAddress (multicastGroup1, multicast_port1)));
onoffhelper1.SetAttribute("DataRate", DataRateValue(64000));
onoffhelper1.SetAttribute("PacketSize", UintegerValue (429));
onoffhelper1.SetAttribute("OnTime", StringValue ("ns3::ConstantRandomVariable[Constant=120]"));
onoffhelper1.SetAttribute("OffTime", StringValue ("ns3::ConstantRandomVariable[Constant=0]"));
onoffhelper1.SetAttribute("MaxBytes", UintegerValue (maxBytes));
ApplicationContainer stream = onoffhelper1.Install (Streamer_Node.Get (0));

// Tell the application when to start and stop.
stream.Start (Seconds (2.));
stream.Stop (Seconds (100.1));

// Create an optional packet sink to receive these packets
PacketSinkHelper sink ("ns3::UdpSocketFactory",
                        InetSocketAddress (Ipv4Address::GetAny (), multicast_port1));
 ApplicationContainer streamb = sink.Install (ssNodes1.Get(0)); //
// Start the sink
streamb.Start (Seconds (5.0));
//streamb.Stop (Seconds (25.0));
streamb.Stop (Seconds (100.2));
```

Appendix D: Performance metrics computation in NS-3.

```
    float throughput_MAC = stats->second.rxBytes * 8.0 / (stats->second.timeLastRxPacket.GetSeconds()-stats-
>second.timeFirstTxPacket.GetSeconds())/1000;
    t = Simulator::Now();//check
    printf("Throughput at MAC1 : %f Kbps.\n",throughput_MAC);
    fprintf(fp_4,"%f\t",t.GetSeconds());
    fprintf(fp_4,"%f\n",throughput_MAC);

    float Average_delay_MAC = (stats->second.delaySum).GetSeconds()/(double (stats->second.rxPackets));
    t = Simulator::Now();
    printf("Average Delay at MAC1 : %f s.\n",Average_delay_MAC);
    fprintf(fpD1,"%f\t",t.GetSeconds());
    fprintf(fpD1,"%f\n",Average_delay_MAC);

    float Average_jitter_MAC = (stats->second.jitterSum).GetSeconds()/(double (stats->second.rxPackets - 1));
    t = Simulator::Now();
    printf("Average Jitter at MAC1 : %f s.\n",Average_jitter_MAC);
    fprintf(fpJ1,"%f\t",t.GetSeconds());
    fprintf(fpJ1,"%f\n",Average_jitter_MAC);

    float Sender_bit_rate = (stats->second.txBytes * 8)/(double ((stats->second.timeLastTxPacket -stats-
>second.timeFirstTxPacket).GetSeconds()));
    t = Simulator::Now();
    printf("Sender_bit_rate : %f bps.\n",Sender_bit_rate);
    fprintf(fpSB1,"%f\t",t.GetSeconds());
    fprintf(fpSB1,"%f\n",Sender_bit_rate);

    float Actual_Packet_loss = (stats->second.txPackets - stats->second.rxPackets)/(double (stats->second.txPackets));
    t = Simulator::Now();
    printf("Actual_packet_loss : %f bps.\n",Actual_Packet_loss);
    fprintf(fpPL1,"%f\t",t.GetSeconds());
    fprintf(fpPL1,"%f\n",Actual_Packet_loss);
```

Appendix E: Computation of throughput at the application layer.

```
Time t = Simulator::Now();
printf("Current time:%f seconds.\n",t.GetSeconds());

//connection 1
int bytesTotal = sink_a->GetTotalRx();
float throughput = (bytesTotal*8.0)/1000/t.GetSeconds();
printf("Throughput at sink 1 : %f Kbps.\n",throughput);
fprintf(fp_1,"%f\t",t.GetSeconds());
fprintf(fp_1,"%f\n",throughput);

//connection 2
bytesTotal = sink_b->GetTotalRx();
t = Simulator::Now();
throughput = (bytesTotal*8.0)/1000/t.GetSeconds();
printf("Throughput at sink 2 : %f Kbps.\n",throughput);
fprintf(fp_2,"%f\t",t.GetSeconds());
fprintf(fp_2,"%f\n",throughput);

//connection 3
bytesTotal = sink_c->GetTotalRx();
t = Simulator::Now();
throughput = (bytesTotal*8.0)/1000/t.GetSeconds();
printf("Throughput at sink 3 : %f Kbps.\n",throughput);
fprintf(fp_3,"%f\t",t.GetSeconds());
fprintf(fp_3,"%f\n",throughput);
```

Appendix F. Set up of virtual network capacities in NS-3.

```
csmaASN_BS1.SetChannelAttribute ("DataRate", DataRateValue (DataRate (2000000)));
csmaASN_BS1.SetChannelAttribute ("Delay", TimeValue (MilliSeconds (2)));
csmaASN_BS1.SetDeviceAttribute ("Mtu", UintegerValue (1500));


csmaASN_BS2.SetChannelAttribute ("DataRate", DataRateValue (DataRate (10000000)));
csmaASN_BS2.SetChannelAttribute ("Delay", TimeValue (MilliSeconds (2)));
csmaASN_BS2.SetDeviceAttribute ("Mtu", UintegerValue (1500));

csmaASN_BS3.SetChannelAttribute ("DataRate", DataRateValue (DataRate (5000000)));
csmaASN_BS3.SetChannelAttribute ("Delay", TimeValue (MilliSeconds (2)));
csmaASN_BS3.SetDeviceAttribute ("Mtu", UintegerValue (1500));
```