

WiMAX Spectrum Virtualization and Network Federation

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Dedication

I would first like to dedicate this thesis to Jehovah the Almighty God, my darling wife Ifeanyichukwu, my beloved daughter Inioluwa and my loving parents Sir Festus Ibukun and Lady Bethel Ufuoma Ogunleye.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Signed by candidate

August 2016

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Abstract

Spectrum management in wireless broadband networks as regards its cost and its efficient usage, has posed a huge challenge for mobile network operators. Traditionally, network operators had exclusive rights to access the band of spectrum allocated to them, but with the high price of spectrum license, it is becoming necessary to find alternative ways to use and access spectrum more efficiently. Resource virtualization is a method which has been extensively adopted in hardware computing for creating abstract versions of physical hardware resources and it has proven to be a powerful technique for customized resource provision and sharing. This idea of resource virtualization is gradually being transferred into the domain of wireless mobile network resource management but the ideas around it are still evolving.

Since spectrum is an important wireless network resource, it is imperative to provide an efficient and cost effective means for the resource to be accessed and utilized. Therefore the idea of *spectrum virtualization* is investigated in this research as a possible solution to this problem. To expand on the notion of spectrum virtualization, this research further explores the idea of *network federation*. Network Federation involves the interconnection of diverse network components to be operated as a single seamless network. This will enable them share their network resources while the networks are geographically dispersed and managed by different network operators. To fully implement these concepts there is a need for a well-developed network framework.

This research proposes two novel architectures for spectrum virtualization and network federation using the WiMAX (Worldwide Interoperability for Microwave Exchange) wireless broadband technology. The proposed WiMAX spectrum virtualization architecture introduces a novel entity known as the Virtual Spectrum Hypervisor (VS-Hypervisor). This VS-Hypervisor bears the responsibility of spectrum management and virtualization within the WiMAX framework. In the implementation of WiMAX network federation, the novel architecture enables the cooperative existence of multiple WiMAX base-stations having virtualization capabilities with overlapping cellular coverage areas for the purpose of sharing

their spectrum resources. In this architecture, a novel federation control plane known as the Virtual Spectrum Exchange Locale (VSEL) is proposed. The VSEL facilitates the VS-Hypervisors in the federated physical base-stations to be able to negotiate and exchange spectrum between themselves to match their spectrum needs.

The architectures for WiMAX spectrum virtualization and network federation was modelled and implemented using the OPNET Modeler. Results obtained validated their efficacy with respect to the effective management of the wireless network spectrum. Therefore this proposed network architectures would help network operators optimize their radio networks.

Contents

Contents	vii
List of Figures	xi
List of Tables	xiv
List of Abbreviations	xv
Chapter 1 Introduction	1
1.1 Background.....	1
1.2 Related Work	3
1.2.1 WiMAX Virtualization Based on vBTS Architecture	3
1.2.2 WiMAX Virtualization using Network Virtual Substrate (NVS).....	4
1.2.3 LTE eNodeB Virtualization	6
1.2.4 Spectrum Virtualization Layer.....	7
1.2.5 Spectrum Slicing using Picasso	8
1.2.6 Federation of Virtual Networks	10
1.3 Problem Statement	11
1.3.1 Research Questions	12
1.4 Research Hypotheses	12
1.5 Research Methodology	13
1.6 Research Contributions	13
1.7 Publication(s)	14
1.8 Thesis Organisation	14
Chapter 2 Mobile WiMAX PHY & MAC Layer	15
2.1 Introduction.....	15
2.2 WiMAX Standard Evolution	15
2.3 Features of Mobile WiMAX.....	16
2.4 WiMAX Physical Layer	18
2.4.1 OFDM Fundamentals.....	18
2.4.2 OFDMA Basics.....	21
2.4.3 OFDMA Sub-Channelization	21
2.4.3.1 Partially Used Sub-Channelization (PUSC) Permutation Scheme.....	22
2.4.3.1.1 Downlink PUSC.....	22

2.4.3.1.2	Uplink PUSC.....	25
2.4.4	Scalable OFDMA.....	26
2.4.5	Mobile WiMAX Frame Structure.....	27
2.5	Mobile WiMAX MAC-Layer.....	29
2.5.1	Channel Access Method.....	30
2.5.2	WiMAX Quality of Service.....	30
2.6	Chapter Relevance.....	32
2.7	Summary.....	33
Chapter 3	WiMAX Virtual Spectrum Simulation Plan Design.....	35
3.1	Introduction to OPNET Modeler.....	35
3.2	The OPNET Environment.....	36
3.2.1	OPNET Modeler Editors.....	36
3.3	Overview of OPNET WiMAX Model Suite.....	37
3.3.1	Model Features.....	37
3.3.2	OPNET WiMAX Model Structure.....	39
3.3.2.1	Project Model.....	39
3.3.2.2	Node Model.....	40
3.3.2.3	OPNET Process Models.....	42
3.3.2.4	Force and Unforced States.....	43
3.3.2.5	WiMAX Process Models.....	44
3.3.3	OPNET WiMAX Configuration Object.....	45
3.3.4	OPNET Application Configuration Node.....	46
3.3.5	OPNET Profile Configuration.....	47
3.4	Spectrum Virtualization Implementation on OPNET.....	48
3.5	VS-Hypervisor Design.....	50
3.5.1	VS-Hypervisor Node Model.....	51
3.5.2	VS-Hypervisor Process Model.....	53
3.5.2.1	VS-Hypervisor Process Model for Spectrum Virtualization.....	53
3.5.2.2	VS-Hypervisor Spectrum Access.....	57
3.5.2.3	VS-Hypervisor Process Model for Federation.....	60
3.6	Software Testbed Qualitative Description.....	62
3.7	Summary.....	63
Chapter 4	WiMAX Spectrum Virtualization Implementation.....	65
4.1	Explaining the Concept of Virtualization.....	65

4.2	Virtualization Techniques	67
4.2.1	Guest Operating System Virtualization	67
4.2.2	Hypervisor Virtualization	68
4.2.3	Full Virtualization	68
4.2.4	Para-virtualization	69
4.3	Network Virtualization	70
4.3.1	4WARD Project	72
4.4	Wireless Virtualization	73
4.4.1	Perspectives of Wireless Virtualization	74
4.4.1.1	<i>Flow-based</i> and <i>Data</i> Wireless Virtualization	74
4.4.1.2	<i>Protocol-Based</i> Wireless Virtualization	75
4.4.1.3	<i>RF Frontend</i> and <i>Spectrum-based</i> Wireless Virtualization	75
4.4.2	WiMAX Spectrum Virtualization	75
4.4.2.1	Spectrum Virtualization Architecture	76
4.4.2.2	Subcarriers Estimation	78
4.4.2.3	VS-Hypervisor Spectrum Management	79
4.4.2.4	Spectrum allocation based on FFT and Bandwidth Mapping	79
4.4.2.5	VS-Hypervisor Operational Characterization	88
4.5	Performance Analysis of WiMAX Spectrum Virtualization	91
4.5.1	SLA Contract Based Analysis	92
4.5.2	Traffic Based Analysis and Results	96
4.5.2.1	Voice Traffic Configuration in OPNET	98
4.5.2.2	Voice Traffic Result & Analysis	99
4.5.2.3	Video Traffic Configuration in OPNET	101
4.5.2.4	Video Traffic Result & Analysis	102
4.5.2.5	Data Traffic Configuration in OPNET	104
4.5.2.6	Data Traffic Result and Analysis	106
4.6	Conclusion	108
4.7	Summary	109
Chapter 5	WiMAX Network Federation with Virtualization	111
5.1	Introduction	111
5.2	The Concept of Federation and Virtualization in Networks	111
5.3	WiMAX Network Federation Architecture	113
5.3.1	Federation Algorithm at the VSEL	114

5.4	Network Federation Requirements	117
5.5	Implementation of Network Federation.....	117
5.5.1	Simulation Scenario	118
5.6	Results and Analysis	119
5.7	A Novel Testbed for the Implementation of WiMAX Spectrum Virtualization and Network Federation	127
5.8	Conclusion	128
5.9	Summary.....	129
Chapter 6	Conclusion and Future Work.....	131
6.1	Conclusion	131
6.1.1	Research Discussion and Limitations	132
6.2	Theoretical Contributions and Implications.....	134
6.3	Future Work.....	135
References	137
Appendix A:	Global Repository Access Code in OPNET	A-1
Appendix B:	OPNET WiMAX PHY Data Structure Code	B-1
Appendix C:	FFT Size Index Function in OPNET.....	C-1

List of Figures

Figure 1.1	Conceptual Design of WiMAX vBTS [11].	3
Figure 1.2	Design Model of NVS [12].	5
Figure 1.3	LTE eNodeB Virtualization [3] (based on [13]).	6
Figure 1.4	Spectrum Virtualization Layer (SVL) Architecture [16].	8
Figure 1.5	Picasso Architecture [21].	9
Figure 1.6	SEP Architecture for Network Federation [22].	10
Figure 1.7	Thesis Methodology.	13
Figure 2.1	OFDM Architecture with Cyclic Prefix [35].	18
Figure 2.2	Cyclic Prefix Construction [5].	20
Figure 2.3	Structure of OFDMA Sub-carriers [5].	21
Figure 2.4	DL-PUSC Subcarrier Permutation [30].	24
Figure 2.5	UL-PUSC Subcarrier Permutation [30].	25
Figure 2.6	Frame Structure for WiMAX OFDMA.	28
Figure 2.7	WiMAX Protocol Stack.	29
Figure 3.1	Hierarchical OPNET Editors.	36
Figure 3.2	A WiMAX Network model in OPNET Project Editor.	39
Figure 3.3	WiMAX Subscriber Station Node Model [52].	40
Figure 3.4	OPNET's WiMAX Base-Station MAC Node Model [49].	41
Figure 3.5	Graphical Representation of Forced and Unforced States [52].	43
Figure 3.6	OPNET WiMAX MAC and Base-station Control Process Models.	44
Figure 3.7	OPNET WiMAX Configuration Object.	46
Figure 3.8	OPNET Application Configuration Node.	47
Figure 3.9	OPNET Profile Configuration.	48
Figure 3.10	Spectrum Virtualization Implementation Reference Model in OPNET.	49
Figure 3.11	VS-Hypervisor Node Model.	51
Figure 3.12	Invoked External C-code files by VS-Hypervisor Node Model.	52
Figure 3.13	Invocation of the VS-Hypervisor Process Model by the Node Model.	52
Figure 3.14	Statistics Configuration on the VS-Hypervisor.	53
Figure 3.15	VS-Hypervisor Process Model for Spectrum Virtualization.	54
Figure 3.16	VS-Hypervisor State Variables declaration in the SV block.	54
Figure 3.17	Header File Declaration and Function Prototyping in the Header Block (HB).	55

Figure 3.18 VS-Hypervisor Function Definitions in Function Block (FB).....	56
Figure 3.19 VS-Hypervisor Header File and External C-Code Files.	57
Figure 3.20 VS-Hypervisor Sequence Diagram.	58
Figure 3.21 WiMAX Federation Process Model.	60
Figure 3.22 Sequence Diagram of VS-Hypervisor Federation.	61
Figure 4.1 A Basic Virtual Machine Monitor.	66
Figure 4.2 Guest OS Based Virtualization.	68
Figure 4.3 Full Virtualization.	69
Figure 4.4 Para-Virtualization.	70
Figure 4.5 Basic Network Virtualization Model [68].	72
Figure 4.6 4WARD Provider Roles [78].	73
Figure 4.7 WiMAX Spectrum Virtualization Architecture.	77
Figure 4.8 Frame Scanning Function Code.	79
Figure 4.9 FFT Mapping Flowchart.	81
Figure 4.10 FFTMap and BWMap Function call in OPNET.	82
Figure 4.11 Bandwidth Mapping Algorithm.	83
Figure 4.12 FFT & BW Mapping Code in OPNET.	84
Figure 4.13 Spectrum Allocation Algorithm.	86
Figure 4.14 Spectrum and Bandwidth Allocation for FA Contract in OPNET.	87
Figure 4.15 Spectrum and Bandwidth Allocation for DA Contract in OPNET.	87
Figure 4.16 Spectrum and Bandwidth Allocation for BEA Contract in OPNET.	87
Figure 4.17 VS-Hypervisor Time Delay Block.	88
Figure 4.18 VS-Hypervisor Input Information.	88
Figure 4.19 VS-Hypervisor Output Information.	89
Figure 4.20 VS-Hypervisor Time-Flow Structure.	89
Figure 4.21 VS-Hypervisor Input/output Mapping.	90
Figure 4.22 WiMAX Spectrum Virtualization Model.	91
Figure 4.23 Spectrum Allocation per Virtual Base-station.	94
Figure 4.24 Spectrum Utilization per Virtual Base-station.	94
Figure 4.25 Overall Spectrum Utilization.	95
Figure 4.26 Average Utilized Bandwidth per Virtual Base-station.	96
Figure 4.27 VB1 OPNET Voice Configuration.	99
Figure 4.28 VB1 Average Voice (VoIP) Throughput.	100
Figure 4.29 VB1 Voice (VoIP) Average End-to-End Delay.	101

Figure 4.30 VB2 OPNET Video Traffic Configuration	102
Figure 4.31 VB2 Video (Video Streaming) Average downlink Throughput	103
Figure 4.32 VB2 Video Streaming Average End-to-End delay	103
Figure 4.33 VB3 OPNET Web Browsing Data Traffic Configuration	104
Figure 4.34 OPNET HTTP Page Properties	105
Figure 4.35 HTTP Server Selection Sub-attributes Configuration	106
Figure 4.36 VB3 Average Data (Web browsing with multimedia) Downlink Throughput	107
Figure 4.37 Average Web Browsing Downlink End-to-End Delay	107
Figure 5.1 Network Federation Illustration	112
Figure 5.2 WiMAX Network Federation Architecture	113
Figure 5.3 WiMAX Federation VSEL Algorithm	115
Figure 5.4 WiMAX Network Federation Function in OPNET	116
Figure 5.5 WiMAX Federation Simulation Setup in OPNET	118
Figure 5.6 Available Spectrum for BS 1 & 2 Without Federation	120
Figure 5.7 Throughput for BS 1 & 2 Without Federation for Video Traffic	121
Figure 5.8 Spectrum Changes in BS1 & BS2 with Federation	121
Figure 5.9 Throughput of BS1 & BS2 With Federation for Video Traffic	122
Figure 5.10 BS1 Before and After Federation Throughput for Video Traffic	122
Figure 5.11 BS1 Before and After Federation Average Throughput for Video Traffic	123
Figure 5.12 BS1 Before and After Federation Average Delay for Video Traffic	123
Figure 5.13 Throughput Change in BS2 After Federation for Video Traffic	124
Figure 5.14 BS1 Before and After Federation Average Throughput for Voice Traffic	124
Figure 5.15 BS1 Before and After Federation Average Delay for Voice Traffic	125
Figure 5.16 BS1 Before and After Federation Average Throughput for Data Traffic	126
Figure 5.17 BS1 Before and After Federation Average Delay for Data Traffic	126

List of Tables

Table 2.1 Summary of IEEE 802.16 Standards.	17
Table 2.2 DL-PUSC Sub-carrier Permutation Parameters [30].	23
Table 2.3 S-OFDMA Parameters.	26
Table 2.4 WiMAX QoS Classification.	32
Table 3.1 Purpose of the Hierarchical OPNET Editor [52].	37
Table 3.2 OPNET WiMAX Features.	38
Table 3.3 WiMAX Node Models in OPNET.	41
Table 3.4 Process Model Objects [52].	43
Table 3.5 WiMAX Process Models Description [52].	45
Table 4.1 Types of Hypervisors.	67
Table 4.2 Strength and Limitation of Network Virtualization Projects.	71
Table 4.3 Broadband Wireless Applications Traffic Parameters (from [30]).	92
Table 4.4 Simulation Parameters & Configuration for SLA Contract Analysis.	93
Table 4.5 Simulation Parameters & Configuration for Traffic Based Analysis.	97
Table 5.1 Simulation Parameters for WiMAX Network Federation using Video Traffic.	119

List of Abbreviations

ACK	Acknowledgement
ADC	Analogue-to-digital Converter
AMC	Adaptive Modulation and Coding
API	Application Program Interface
ARP	Address Resolution Protocol
ARQ	Automatic Repeat Request
ASN	Access Service Network
BE	Best Effort
BEA	Best Effort Allocation
BPSK	Binary Phase-shift Keying
BW	Bandwidth
CAPEX	Capital Expenditure
CID	Connection Identification
CP	Cyclic Prefix
CQICH	Channel Quality Indicator Channel
CS	Convergence Sublayer
DA	Dynamic Allocation
DC	Direct Current

DL-MAP	Downlink Medium Access Protocol
DL-PUSC	Downlink Partial Usage of Sub-channels
DOCSIS	Data over Cable Service Interface Specification
DSP	Digital Signal Processing
eNodeB	Evolved Node B
ErtPS	Extended real-time Polling Service
FA	Fixed Allocation
FB	Function Block
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FFT	Fast Fourier Transform
FN	Future Network
FSA	Frequency Spectrum Allocation
FTP	File Transfer Protocol
GK	Gate-keeper
GW	Gateway
HB	Header Block
HD	Higher Definition
H-FDD	Half-Duplex Frequency Division Duplexing
HTML	Hypertext Markup Language
HTTP	Hyper-Text Transfer Protocol

IBM	International Business Machine
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IMT-Advanced	International Mobile Telecommunications-Advanced
InP	Infrastructure Provider
ISI	Inter-symbol Interference
ISP	Internet Service Provider
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
LOS	Line-of-Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAN	Metropolitan Area Network
MAP	Medium Access Protocol
MIMO	Multiple-Input Multiple-Output
MNO	Mobile Network Operator
MPDU	MAC Packet Data Units
MS	Mobile Station
MSDU	MAC Service Data Unit
MVNO	Mobile Virtual Network Operator
NIC	Network Interface Card

NLOS	Non-Line-of-Sight
nrtPS	None real-time Polling Service
NSP	Network Service Provider
NVS	Network Virtualization Substrate
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
OS	Operating System
OSI	Open System Interconnection
PCF	Point Coordination Function
PDU	Packet Data Unit
PHY	Physical Layer
PRB	Physical Resource Block
PSM	Power Saving Mode
PV	Para-Virtualization
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-shift Keying
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RTG	Receive/Transmit Transition Gap

rtPS	Real-time Polling Service
RX	Receive
SDN	Software Defined Radio
SE	Standard Error
SEP	Slice Exchange Point
SFID	Service Flow Identifier
SLA	Service Level Agreement
S-OFDMA	Scalable Orthogonal Frequency Division Multiple Access
SON	Self-organizing Network
SP	Service Provider
SS	Subscriber Station
STD	State Transition Diagram
SVL	Spectrum Virtualization Area
TCP/IP	Transmission Control Protocol and Internet Protocol
TDD	Time Division Duplexing
TTG	Transmit/Receive Transition Gap
TX	Transmit
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
UL-MAP	Uplink Media Access Protocol
VB	Virtual Base-station

vBTS	Virtual Base-station Substrate
VM	Virtual Machine
VMM	Virtual Machine Monitor
VNO	Virtual Network Operator
VNP	Virtual Network Provider
VoIP	Voice over Internet Protocol
VSEL	Virtual Spectrum Exchange Locale
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1 Introduction

1.1 Background

The radio frequency spectrum which ranges from 3 KHz to 300 GHz is generally accepted to be a scarce resource and it is therefore not inexhaustible. Consequently, it has become necessary for it to be properly managed to safeguard its efficient and equitable access for the services that use it, for instance, the services rendered in wireless broadband networks. In recent times, there has been an exponential increase in the number of wireless devices with greater demand for voice, data and video use of the spectrum. This increase in demand trend is expected to continue in the coming future. This growing demand possess a serious challenge for mobile network operators (MNOs) in the context of spectrum management.

Spectrum virtualization is one of the newest frontiers of innovation in wireless cellular networks particularly in the area of spectrum management and it has recently gotten a considerable amount of research application in some 4G wireless technologies [1]. The principles of virtualization, especially spectrum virtualization (in its strictest sense), has not been extensively applied and expanded to accommodate the competing 4G technologies like the Worldwide Interoperability for Microwave Access (WiMAX). Wireless network virtualization is one of the key enabling technologies that will ensure the efficient use of the wireless spectrum, an idea that is currently being considered in the design of 5G networks [2].

The generic idea of spectrum virtualization falls under the umbrella of *wireless virtualization*, an emerging paradigm, which can be viewed from various perspectives. The various ways by which wireless virtualization can be considered include but not entirely limited to the virtualization of the wireless network infrastructure, mobile network virtualization and wireless access virtualization. To define wireless virtualization will be to describe it as the sharing and abstraction of wireless access resources [3]. Therefore, relating this to spectrum virtualisation

obviously implies that spectrum virtualization means the sharing and abstraction of wireless spectrum (air interface) both in the time and frequency domains.

One of the major reasons for which WiMAX is the network technology chosen as the study case for this research, is because it is a matured 4G technology [4] with better specifications especially when compared with the Long Term Evolution (LTE). Mobile WiMAX is based on the IEEE802.16e standard. It adopts the use of the Orthogonal Frequency Division Multiplexing Access (OFDMA) technique specifically the Scalable-OFDMA (S-OFDMA) in allocating its time-frequency spectrum resources to its users. S-OFDMA enables a flexible allocation of spectral resources for a wide range of channel bandwidths (1.25 – 20MHz) [5]. The scalability achieved in S-OFDMA is actualized by adjusting its Fast Fourier Transform (FFT) size (in the range between 128 – 2048) while the sub-carrier frequency spacing is 10.94 kHz [5].

Considering the unique air interface design of mobile WiMAX, particularly the scalable usage of OFDMA, it is very clear that applying directly any generalised virtualization methods for the virtualization of WiMAX's spectrum will not be easily applicable. Hence there is a need for an exclusive spectrum virtualization method that caters for its specific air interface features which is one of the focus of this research.

Another emerging area of research that has been closely linked to the idea of network virtualization is the area of network federation. Network federation is not a new concept and its principles have been applied extensively in the field of computer networks [6], [7], [8], [9], particularly the federation of virtualised network domains. According to [10], *federation* can be described as the aggregation of isolated administrative resources into a common pool which enables the more efficient utilization of resources.

In this research, besides from the virtualization of the WiMAX spectrum, the idea of network federation is explored in relation to wireless spectrum management. In this context, the federation of wireless virtual networks can be interpreted as the interconnection of independently owned mobile network base-stations which have slices (virtual networks) in such a way that permits them to share radio spectrum amongst themselves and ultimately decide the amount of spectrum that will be allocated to their individual slices.

To ensure the feasibility of the network federation of WiMAX base-stations that offer virtualization for the purpose of spectrum sharing, this research assumes that the cellular coverage areas of the WiMAX base-stations are co-located or overlapped and therefore are within the same geographical region.

1.2 Related Work

This section discusses various research works that have been done in the areas that covers: WiMAX network virtualization, spectrum virtualization and wireless network federation. The essence is to identify the gaps that forms the basis of this research work.

1.2.1 WiMAX Virtualization Based on vBTS Architecture

Gautam Bhanage et al [11] of the WINLAB of Rutgers University and NEC Laboratories America, proposed a virtual base transceiver system (vBTS) for WiMAX that allows multiple Mobile Virtual Network Operators (MVNOs) to share the same network infrastructure. According to [11] since the design of the physical WiMAX base-station is proprietary, therefore, the vBTS has to be located outside of the base-station. Consequently the proposed vBTS architecture is a software emulation of a full WiMAX base-station using virtual machine (VM) instances as shown in Figure 1.1 below.

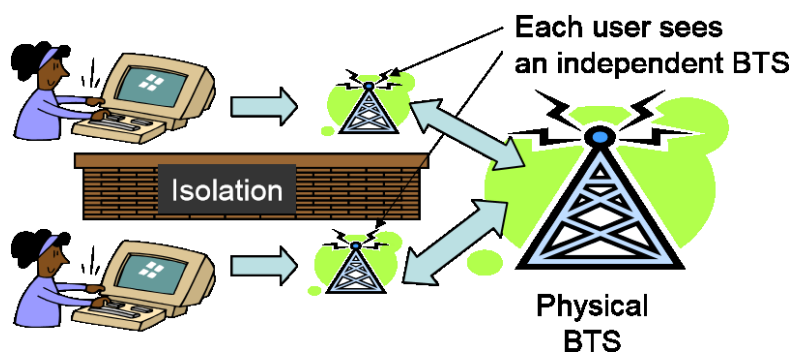


Figure 1.1 Conceptual Design of WiMAX vBTS [11].

The WiMAX Access Service Network (ASN) gateway is modified to forward traffic coming from the individual vBTS to the physical WiMAX base-station. The drawback with [11] is that there is limitation in the isolation of the vBTS as well as their access to the radio spectrum of the physical base-station. In addition, there are no specifics on how the radio spectrum is allocated or shared between the individual vBTS both in the frequency and time domain. Also, no distinctive modification to the WiMAX Medium Access Control (MAC) scheduler was made for scheduling spectrum to the individual vBTS. Their approach to virtualization was primarily *flow-level scheduling*. In contrast, this research approaches WiMAX spectrum virtualization purely from the *slice-level scheduling* of the radio spectrum and proposes a new model on how this can be achieved on a WiMAX network. The difference between flow and slice scheduling will be discussed further in Section 1.2.2.

1.2.2 WiMAX Virtualization using Network Virtual Substrate (NVS)

In a research conducted by Ravi Kokku et al [12], new business models for services with leased networks (SLN) and corporate bundle plans is proposed. The SLNs permits a network operator to control the quality-of service (QoS) of the traffic that flows through the leased network infrastructure. To meet their objective of slice isolation, customization and resource management in WiMAX network virtualization, a framework known as network virtual substrate (NVS) is defined. Comparable to the vBTS described in Section 1.2.1., NVS is described as a flow-based virtualization (i.e. the virtualization of traffic) architecture but unlike vBTS instead of being outside the base-station, it is located within the architecture of the base-station.

Asides its flow-based proficiency, the NVS is also presented as having a slice-level scheduling (i.e. the splitting of wireless resources across different virtual networks) capability with variations known as: *resource-based allocation* and *bandwidth-based allocation* [3], [12]. NVS makes do with WiMAX's existing scheduling algorithm having full control of its functionalities and provides virtualization in the uplink and downlink direction as shown in Figure 1.2.

The challenges with [12] are: 1) the resource-based allocation functionality of NVS, involves allocating portions of WiMAX OFDMA slots to a slice per frame interval to accommodate their service-flows. This implies that only one slice is accommodated per frame and the other slices are made to wait their turn without any guarantees of when next the channel will be made available for them. This is clearly an inefficient way of utilizing the available frequency channels and will result in delays in service flow delivery for slices that are in the waiting. 2) The NVS *bandwidth-based allocation* system has a distorted definition of what bandwidth actually is, whereby, ‘bandwidth’ is explained as the cumulative throughput of the network which is not based on the frequency band [3]. That means services-flows of slices will only be given the aggregated throughput (bandwidth) irrespective of their QoS requirements implying that there will be instances of under-allocation or over-allocation of OFDMA resources which again clearly portrays an inefficient use of spectral resources.

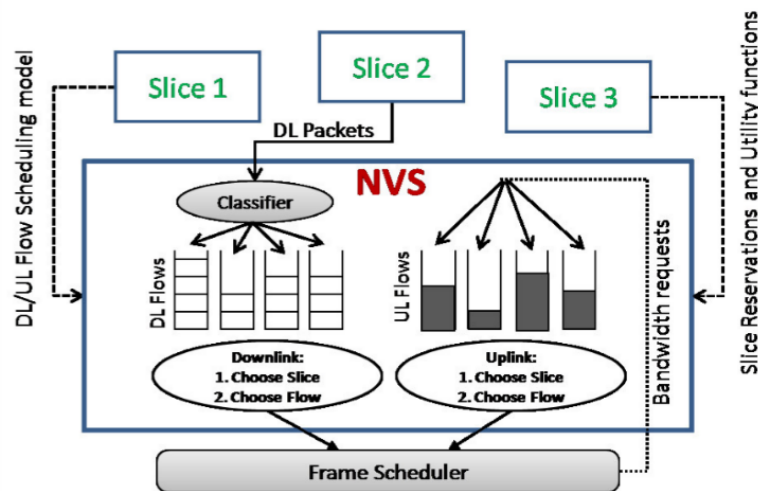


Figure 1.2 Design Model of NVS [12].

In contrast, this research proposes and implements a WiMAX spectrum virtualization system that ensures that all virtual networks have simultaneous access to the spectrum. The spectrum slices are apportioned to meet the individual QoS requirements for the service flows.

1.2.3 LTE eNodeB Virtualization

A virtualization framework for LTE's evolved Node-B (eNodeB) is developed by [13] and it is closely similar to the virtualization design previously discussed in Section 1.2.2. The eNodeB is the base-station equivalent in LTE and it bears the responsibility of scheduling radio resources to user equipment using OFDMA. The radio resource for allocation in this case [13] particularly in the context of LTE is referred to as physical resource blocks (PRBs). To achieve virtualization of the LTE eNodeB (which is done in the downlink direction in [13]), the framework possesses a hypervisor layer that collects the configuration and service level agreement (SLA) contract of each virtual eNodeB owned by an MVNO and then dynamically allocates the PRBs to them individually as shown in Figure 1.3. The word or term *hypervisor* is often referred to as the layer that ensures the isolation of slices in a virtualized infrastructure. It is also denoted to as a virtual machine monitor (VMM) in relation to Computer virtualization [3].

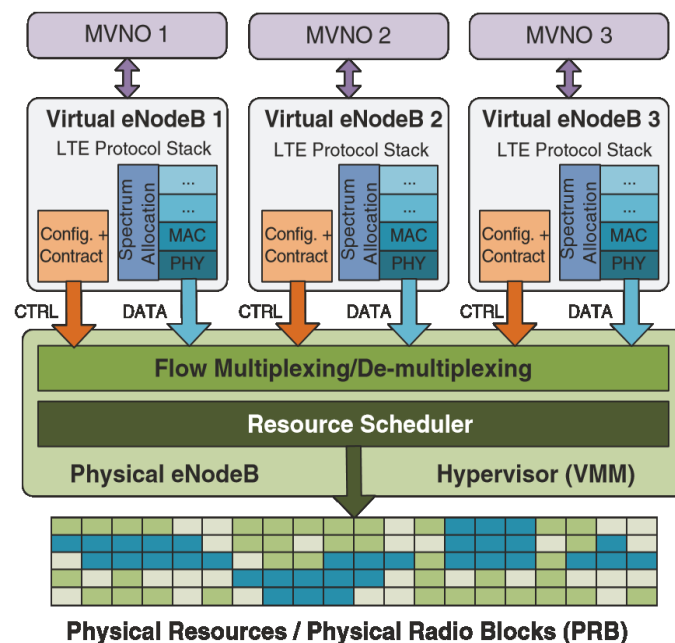


Figure 1.3 LTE eNodeB Virtualization [3] (based on [13]).

The research method carried out by [13] is claimed to be applicable to other wireless broadband technologies like WiMAX but until now there has been no proof to its application. The

framework has the same layered structure similar to the XEN hardware virtualization architecture [14], [15]. This research adopts the same layered structure as was used in [13] [15], specifically the hypervisor layer but the layer has been renamed as the *VS-Hypervisor* (virtual spectrum hypervisor) reflecting its unique ability for virtualizing the wireless spectrum of WiMAX. This is explained further in Chapter 3 & 4.

1.2.4 Spectrum Virtualization Layer

Kun Tan et al in [16], [17] proposed a new method for frequency spectrum allocation (FSA) in existing wireless networks through the introduction of a *spectrum virtualization layer (SVL)* that lies just below the physical layer (PHY) and it is labelled as *Layer 0.5*. This new layer enables FSA functionality in the PHY layer without changing the PHY's design. The two key utilities of SVL are signal reshaping and spectrum enforcement. The objective of the SVL is to bridge/connect traditional wireless PHY normally designed to use fixed frequency bands and bandwidths with FSA's dynamic baseband.

In its full operation, the SVL dissociates the connection between the wireless network PHY and the radio frequency (RF) front-end and it then provides a *virtual baseband* to the PHY layer of the virtual slices that is contiguous with a desired bandwidth. Thereafter, the SVL dynamically reshapes the *virtual baseband signals* into waveforms that corresponds with the real available frequency bands. It then finally transmits them through the RF front-end. At the receiver end, the reverse of the reshaping operation is performed. The SVL architecture is comprises of many components but the major ones are the *spectrum manger*, the *reshaper*, the *mixer* and the *splitter* as depicted in Figure 1.4.

The *spectrum manager's* function is to compute the spectrum allocation for each slice using allocation algorithms and policies. The *spectrum reshaper* ensure that the SVL reshapes the baseband spectrum for each slice to match the physical baseband spectrum. And finally, the *mixer* and *splitter* multiplexes and de-multiplexes the baseband spectrum for each slice before transmission through the radio front-end.

The limitations of the research reported in [16], [17] is that the SVL was only tested on the narrowband short-range wireless technologies (Zigbee and Wi-Fi) and its efficiency and

limitations cannot be verified for wideband long-range wireless broadband technologies. The SVL architecture only considered RF front-ends that are half-duplex, whereas there has been a good amount of research breakthroughs [18], [19], [20] on the use of full-duplex RF frontend transmission which will significantly boost spectrum efficiency. In contrast, this research designs and implements a spectrum virtualization architecture for WiMAX that has software and logical emulations of a full-duplex RF frontend.

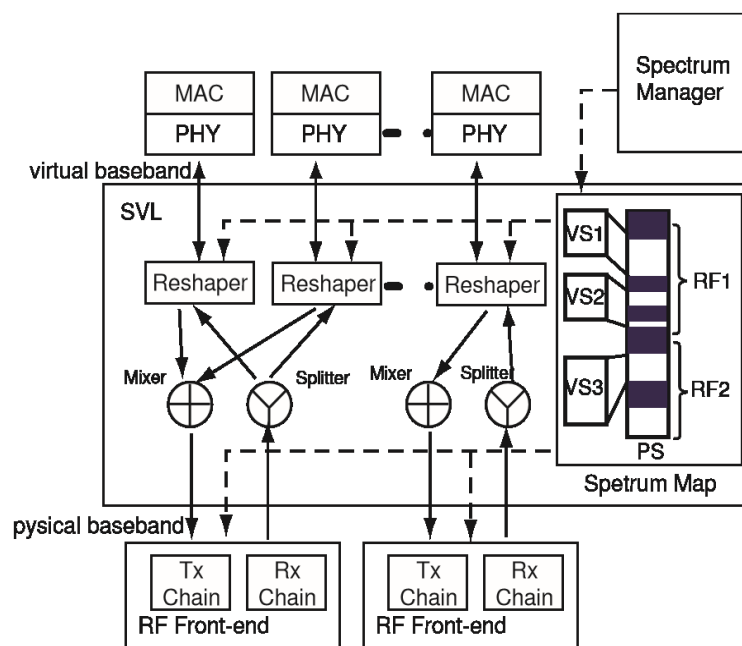


Figure 1.4 Spectrum Virtualization Layer (SVL) Architecture [16].

1.2.5 Spectrum Slicing using Picasso

According to the research paper [21], a novel radio model called Picasso is designed to allow a single RF front-end with a single antenna to concurrently transmit (TX) and receive (RX) various frequency spectrum fragments with reduced leakage in adjacent spectrum. Picasso achieves spectrum isolation among slices through a proposed method called *passive self-interference cancellation*. In [21], it is stated that the main challenge in designing Picasso was the fact that, current radios cannot simultaneously transmit and receive different arbitrary spectrum on a single shared RF front-end and antenna. The reason is because the transmitted signal causes high-powered self-interference which consequently saturates the RX signal, the

analogue-digital converter (ADC) and eventually results in the loss of the received signal. A generalized architecture of Picasso is shown in Figure 1.5.

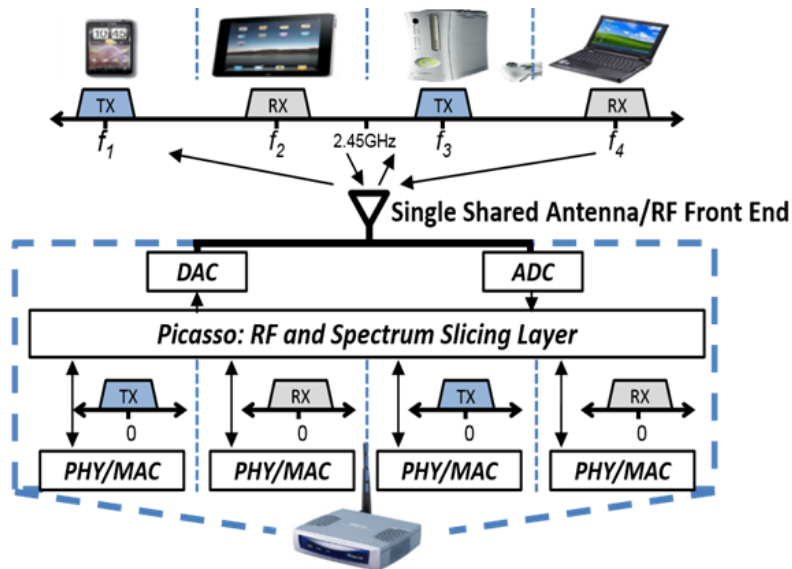


Figure 1.5 Picasso Architecture [21].

The key contribution of [21], is a circuit design that isolates transmit and receive signals at a single antenna by incorporating a circulator and a passive self-interference cancellation system. The range of cancellation is determined by the dynamic range of the ADC. The only major issues with Picasso is that experimental measurements showed that the platform supports four virtual radio slices with minimal signal degradation, but at higher data-rates degradation increases by 10% due to power leakage. Also, the system is tailored more for handheld devices with small antennas but there is not proof that it will work efficiency on larger radio system.

This research assumes the efficacy of the Picasso system for wireless broadband technologies in terms of a full-duplexing antenna and translates its hardware functionalities for spectrum slicing and into a software emulation for a virtualized WiMAX network. The *VS-Hypervisor* (mentioned in Section 1.2.3) serves as the entity that performs the function of a spectrum slicing engine similar in the operation done on Picasso with added sophistication such as: spectrum allocation algorithms based on SLAs.

1.2.6 Federation of Virtual Networks

Recently, a good deal of research work has been put into the federation of virtualized networks. Toshiaki Tarui et al [22] proposed an architecture known as Slice Exchange Point (SEP) for federating multiple heterogeneous virtualized-network platforms for proper slice management. The architecture consists of a federation manager with a universal application program interface (API) for the federation and interworking of the network domains.

The SEP architecture consists of a control and data plane as shown in Figure 1.6. The control plane adopts an exchange model to achieve scalability in order to support multiple virtualized platforms.

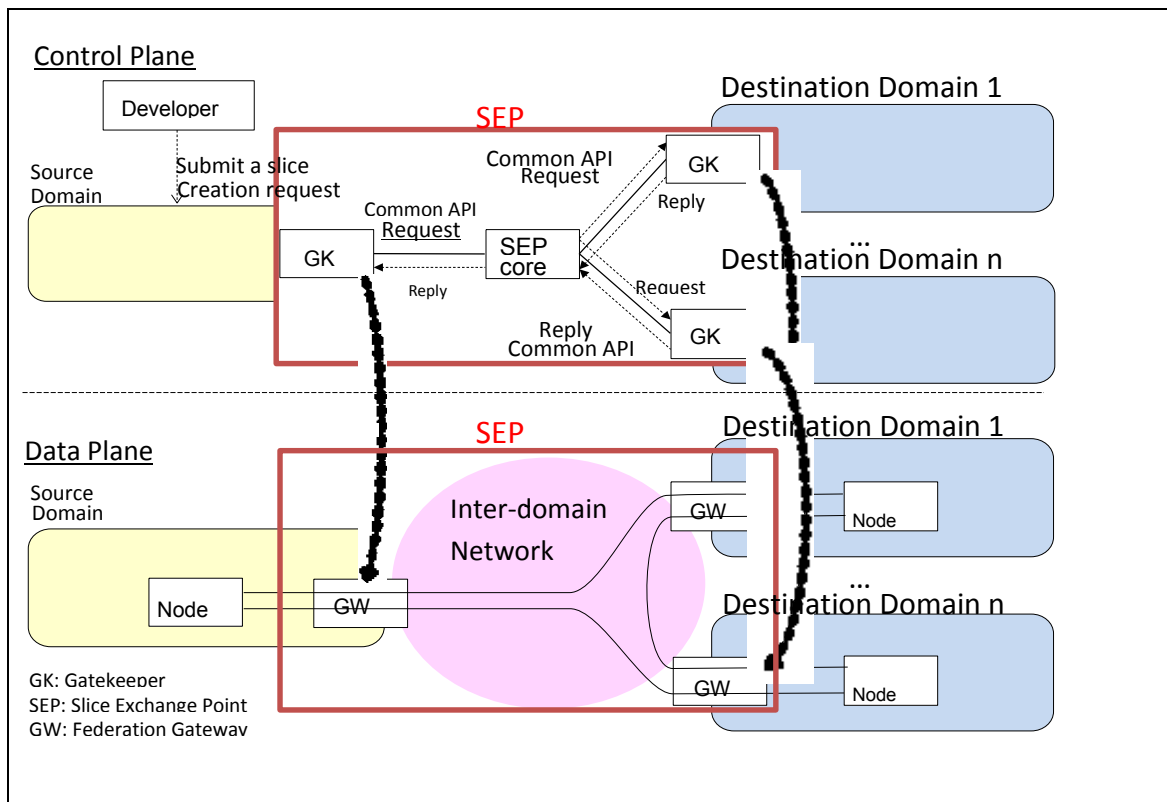


Figure 1.6 SEP Architecture for Network Federation [22].

A universal federation API called the ‘common API’ and the ‘common slice definition’ (resource specification) are included in its design for the exchange of federation requests. The Data plane on the other hand consist of virtual links connected by gateways (GWs). Its major

function is to convert packet formats (protocols, network parameters, etc.) between intra- and inter-domain substrate. The GK (Gate Keeper) on the control plane functions as a manager of inter-domain network resources. The GKs on both ends of the inter-domain link negotiates parameters through the common-API request and reply.

The work done by [22] can be regarded as a reference model for the federation of virtualized heterogeneous networks. In contrast to works previously done wireless network federation, this research proposes a novel functional architecture which is developed for the federation of co-located WiMAX networks for spectrum sharing. The *VS-hypervisor* mentioned in Sections 1.2.3, 1.2.4 and 1.2.5 is extended with additional blocks and functionalities which also includes control plane capabilities to enable inter-base-station negotiation of MVNOs for spectrum sharing. Details on this are explained in Chapter 5.

1.3 Problem Statement

Currently, it appears that the LTE has won the fight for 4G evolution in the mobile operator space especially in most parts of the developed world markets [23] but that has not necessarily led to the demise of WiMAX. In spite of the stiff competition that WiMAX faces, it still serves as better option for private industries because it comes in frequency bands available for private network use; an edge it has over its competitors [24]. The WiMAX forum has recently expanded the application of WiMAX to cover areas such as: Smart Grid (WiGRID), Smart Cities, Public Safety, Aviation (AeroMACS) and Oil & Gas [25], [26], [27], [28]. These new applications further opens up the market for new operators hence there is a need to create a more dynamic environment for operators to provide their services with less capital expenditure (CAPEX) and operating expenditure (OPEX).

Also, future generation of mobile networks (e.g. 5G) promises to offer far higher data rates and quality of service than the current 3G and 4G networks. It is anticipated that these networks could take the form of new radio air interfaces, new cellular architectures such as federated heterogeneous networks, wide-area mobile mesh and even the virtualization of the network itself. For all of these ideas to become successful, it is necessary that adequate research be conducted most especially as it relates to performance analysis which will ultimately justify

their practicability and also help in the development of standards. To this end this research summarizes its core problem statement as follows:

- Amongst the pertinent issues affecting the decline in WiMAX network deployment by new operators, is the cost of spectrum as well as the prevailing CAPEX and OPEX. Also there is a need for better innovative spectrum management techniques that will improve the availability of spectrum not only for WiMAX networks but also for future wireless broadband networks.

1.3.1 Research Questions

In defining the scope of inquiry in this research, the following questions are regarded to be important with respect to this thesis:

- How can bandwidth delay product, data throughput and latency be controlled to implement a service level agreement (SLA) grade in virtualized WiMAX networks?
- How will the individual traffic load of the mobile virtual network operators (MVNOs) be mapped into a competitive spectrum?
- To what degree will the WiMAX network spectrum virtualization boost the spectrum requirements between federated network operators?

1.4 Research Hypotheses

This section highlights the hypotheses for this research. They are outlined as follows:

- The ideas pertinent to Hardware system virtualization and network federation models can also be applied to wireless networks like WiMAX and it will set future trends for virtualized wireless network designs and implementation.
- For a fixed cell size of a Virtualized WiMAX network and assuming that the base-station has full-duplex capability at its antennas, irrespective of the number of virtual networks on the physical network infrastructure, appreciable seamless flow of traffic can be achieved.

- Quantitative analysis of a virtualized WiMAX network spectrum will improve and optimize its proper management.

1.5 Research Methodology

This section highlights the methodology adopted in this research. The Figure 1.7 shows a detailed summary of the methodology approach used in this research.

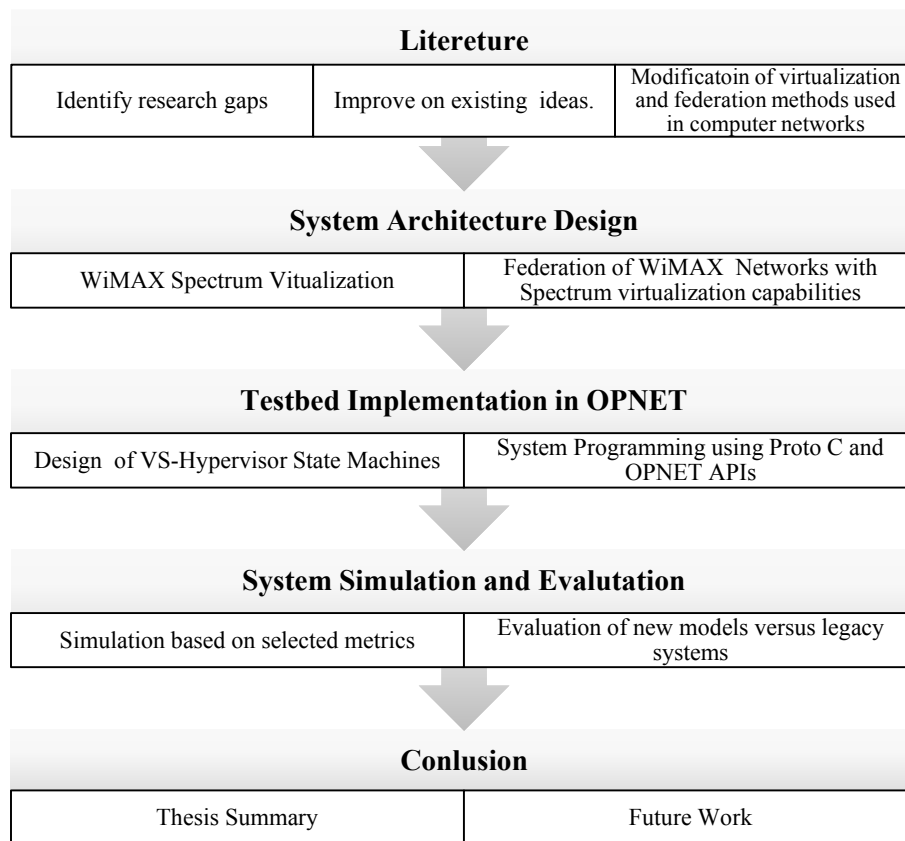


Figure 1.7 Thesis Methodology.

1.6 Research Contributions

The following are the main contributions of this research:

- Development and analysis of a novel architecture for WiMAX network spectrum virtualization utilizing the concept of the “VS-Hypervisor” functioning as the virtual machine monitor.
- Development and analysis of a novel architecture for the federation of WiMAX base-stations having spectrum virtualization capabilities with the “VS-Hypervisor” acting as a control plane entity for spectrum negotiation and allocation between federated base-stations.
- A novel software testbed for the implementation of WiMAX spectrum virtualization and network federation using the OPNET 14.5 Modeler.

1.7 Publication(s)

Listed below is a major publication derived from this research:

- Babatunde S. Ogunleye and Alexandru Murgu, “*A Novel Model for WiMAX Frequency Spectrum Virtualization and Network Federation*”, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 141, Springer 2015, ISBN: 978-3-319-16291-1.

1.8 Thesis Organisation

The rest of this thesis is organized in the following order: **Chapter 2** provides a detailed overview of WiMAX with special focus on the PHY and MAC layers. **Chapter 3** gives a thorough description of the design framework for spectrum virtualization implemented on OPNET. **Chapter 4** describes the details of spectrum virtualization. The novel framework for WiMAX spectrum virtualization is also discussed. Various simulation scenarios and configurations are explained and the results are analysed. **Chapter 5** concentrates on the idea of network federation and the principles that are applied in this thesis. It also describes the novel architecture for WiMAX network federation. Also simulation scenarios and configurations are outlined and results are analysed. Finally, **Chapter 6** discusses the conclusions of this research as well as possible areas for future work.

Chapter 2 Mobile WiMAX PHY & MAC Layer

2.1 Introduction

In this chapter, an overview of Mobile WiMAX technology is presented with more emphasis on the MAC and PHY layer. It is expected that the information provided in this Chapter will provide a detailed understanding of WiMAX's standard, features, and service aspect such as QoS which are relevant from the spectrum management viewpoint.

2.2 WiMAX Standard Evolution

WiMAX technology protocol was originally defined by the Institute of Electrical Electronics Engineers (IEEE) under the IEEE 802.16 group [29]. The IEEE 802.16 Group was formed in 1998 and mandated to develop an air-interface standard for the wireless broadband technologies. The original focus of the group was the development of a Line-of-Sight (LOS) point-to-multipoint wireless broadband system that operates in the 10 GHz - 66 GHz band which resulted in the original IEEE 802.16 standard. Successively, the group produced an amendment to the original standard known as IEEE 802.16a which included None-line-of-sight (NLOS) applications in the 2 GHz -11 GHz band using Orthogonal Frequency Division Multiplexing (OFDM) based PHY layer as well as OFDMA. In 2004 further revisions were made with new additions focusing more on fixed applications and the new standard was called IEEE 802.16-2004 [30].

To solve the problem of nomadic and mobile communication, a new amendment to the existing standard was made in 2005 which is known as the IEEE 802.16e-2005 or Mobile WiMAX. In 2009 further updates to the 802.16e were also made particularly in its frame structure by introducing a super-frame and the support of several advanced multi-antenna techniques

including single and multi-user MIMO (multiple-input multiple-output) in order to meet or exceed the requirements of the IMT-Advanced (International Mobile Telecommunications - Advanced) [31], [32], [33]. IMT-Advanced is a term used by the International Telecommunication Union (ITU) to describe the 4th generation of cellular mobile communication systems.

From the various standards described, one can conclude that WiMAX is a collection of standards which are seemingly not interoperable. To avoid this problem the WiMAX forum in 2001 was formed for the purpose of harmonizing all these standards. Table 2.1 shows a summary of the basic characteristics of the IEEE802.16 standards 802.16-2004 to 802.16-2009. As previously stated, this research is based primarily on the mobile WiMAX standard.

2.3 Features of Mobile WiMAX

Mobile WiMAX standard not only provides scalability in its radio access technology but also in its network architecture. The flexibility it provides in its network architecture allows for various network deployment options and differentiation in the services provided [5]. In this section, the salient features of mobile WiMAX is discussed some of which are listed below:

- **Quality of Service (QoS):** This is the main proposition of the IEEE 802.16 MAC architecture. It ensures end-to-end IP (Internet Protocol) based communication by defining service flows that maps to different service types. Section discusses more on the QoS features of WiMAX.
- **Scalability:** It is designed to scale to different channel bandwidths (previously mentioned in Section 1.1) in accordance with varied worldwide requirements [5].
- **High Data Rates:** Mobile WiMAX supports peak data rates for DL (downlink) up to 144.4Mbps and UL (uplink) with peak rates ranging between 82.9Mbps – 138.2Mbps in the 20MHz channel depending on the modulation and coding scheme used [34].
- **Mobility:** It supports handover schemes that are highly optimized with very low latency especially for services like VoIP to negate service degradation.

Table 2.1 Summary of IEEE 802.16 Standards.

	IEEE802.16-2004	IEEE802.16e-2005	IEEE802.16e-2009
Frequency Band	2GHz – 11GHz	2GHz - 11GHz for fixed; 2GHz - 6GHz for Mobile applications	< 6GHz
MAC Architecture	Point-to-multipoint, mesh	Point-to-multipoint, mesh	Point-to-multipoint, mesh
Transmission Scheme	Single carrier, 256 OFDM or 2,048 OFDM	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1,024, or 2,048 subcarriers	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1,024, or 2,048 subcarriers
Modulation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM
Gross data rate	1Mbps–75Mbps	1Mbps–75Mbps	100Mbps for mobile stations, 1Gbps for fixed
Duplexing Schemes	TDD and FDD	TDD and FDD	TDD and FDD
Channel bandwidths	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	1.75MHz,3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	Scalable from 5 to 40 MHz
Air Interface Designation	WirelessMAN-SC WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMAN	WirelessMAN-SC WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMAN	WirelessMAN-SC WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMAN IMT-Advanced

WirelessMAN-SCa is a single-carrier-based physical layer for a Wireless Metropolitan Area Network (MAN). WirelessMAN-OFDM is an OFDM-based physical layer for Wireless MAN. WirelessMAN-OFDMA is the OFDMA-based physical layer for Wireless MAN. WirelessHUMAN (wireless high-speed unlicensed MAN) is analogous to OFDM-PHY (physical layer) but prioritizes dynamic frequency selection for license-exempt bands.

2.4 WiMAX Physical Layer

The physical layer of mobile WiMAX is based on the OFDM [5] which is a transmission scheme that ensures high-speed data, video and multimedia communication. An extension is the OFDMA for its multiplexing and multiple access operation, for the various data streams from multiple users, both on the DL and UL direction. This section discusses the basics of OFDM and OFDMA that are relevant to spectrum management.

2.4.1 OFDM Fundamentals

OFDM is multicarrier modulation technique that is based on the idea of dividing a given data stream with high bit-rate into several parallel low bit-rate data streams whereby the data-streams are then modulated on separate carriers often known as sub-carriers or tones [30] as depicted in Figure 2.1.

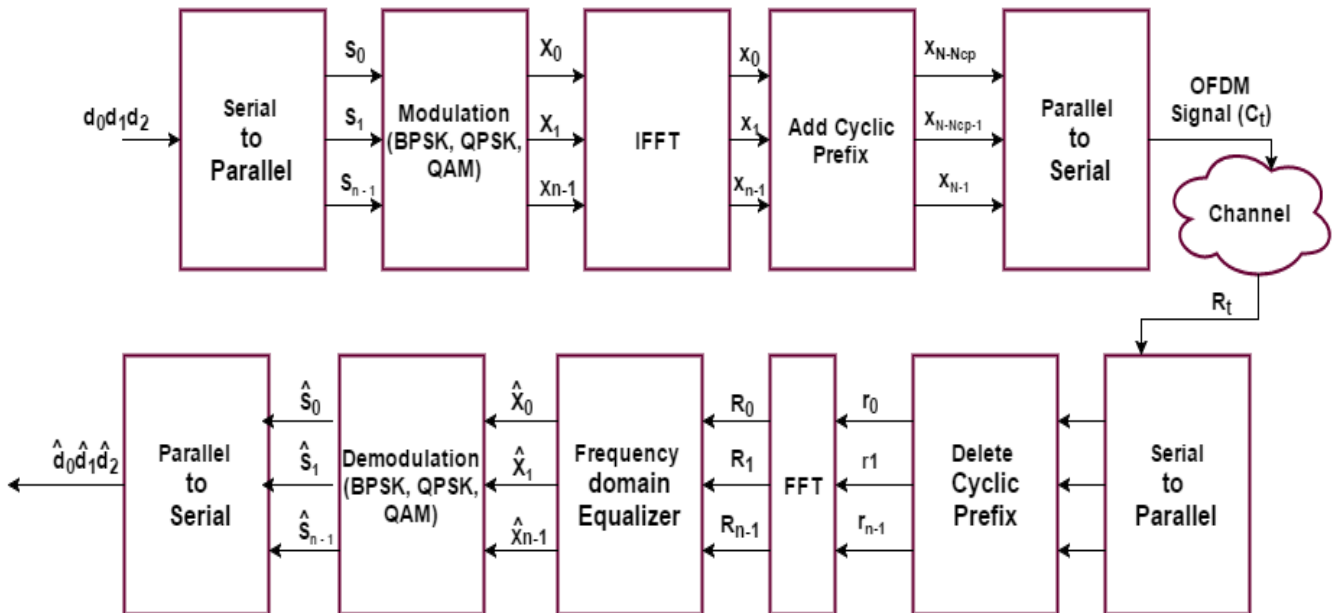


Figure 2.1 OFDM Architecture with Cyclic Prefix [35].

The input stream $[d_0, d_1, d_2]$ of an OFDM system is divided into parallel sub-streams $[S_0, S_1, S_{n-1}]$ with reduced data rates after which each sub-stream is modulated. The modulated sub-

streams $[X_1, X_2, X_{n-1}]$ are then passed through an Inverse Fast Fourier Transform (IFFT) operation which converts the signals from the frequency domain to the time domain $[x_1, x_2, x_{n-1}]$ [36]. The IFFT ensures efficient modulation is achieved and it also enables the use of a large number of sub-streams (sub-carriers with sizes up to 2048) with low complexity [5]. The OFDM signal C_t is generally represented as shown in equation (2.1).

$$OFDM \text{ Signal } C_t = C(t) = \sum_{n=0}^{N-1} S_n(t) \sin 2\pi f_n t \quad (2.1)$$

$S(t)$ = symbols that are modulated using either Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), Quadrature Amplitude Modulation (QAM) etc. [35].

f_n = Orthogonal Frequency.

The representation of FFT [35], [37] is shown by the equation (2.2) below:

$$X(k) = \sum_{n=0}^{N-1} x(n) \sin\left(\frac{2\pi kn}{N}\right) + j \sum_{n=0}^{N-1} x(n) \cos\left(\frac{2\pi kn}{N}\right) \quad (2.2)$$

Whereas the reverse of FFT which is IFFT [35] is represented by the equation (2.3) below:

$$x(n) = \sum_{k=0}^{N-1} X(k) \sin\left(\frac{2\pi kn}{N}\right) - j \sum_{k=0}^{N-1} X(k) \cos\left(\frac{2\pi kn}{N}\right) \quad (2.3)$$

Where N is the length/size of the IFFT/FFT and it defines the total number of sub-carriers present in the OFDM System. For instance, OFDM system with FFT/IFFT size $N = 128$ will produce 128 subcarriers and this also defines the size of the frequency spectrum.

The addition of the cyclic prefix (CP) assists to totally eradicate the Inter-symbol Interference (ISI) as long as the duration of the CP is lengthier than the channel delay spread. The delay spread of a multipath channel can be defined as the standard deviation (or root-mean-square)

value of the delay of reflections in the channel which is proportionally weighted to the energy of the reflected waves [38].

The CP [$X_{N-N_{cp}}$, $X_{N-N_{cp}-1}$, X_{N-1}] can be described as a repetition of the last portion of the data samples that are affixed at the front of the data payload as illustrated in Figure 2.2 below:

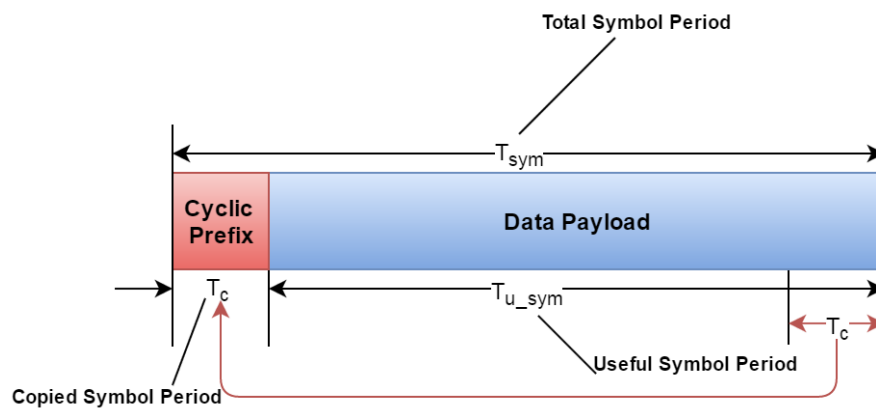


Figure 2.2 Cyclic Prefix Construction [5].

A drawback that is usually associated with the CP is that it creates overheads which ultimately results in bandwidth inefficiency, though which is rather minimal. Since OFDM has a well-designed spectrum, a large portion of the allocated bandwidth is utilized for data transmission which reduces the loss due to inefficiency as a result of the cyclic prefix.

After the insertion of the cyclic prefix, the signal goes through a parallel to serial converter before being transmitted through the wireless channel. The received signal then goes serial to parallel converter and then through the cyclic prefix is removed process module. After the cyclic prefix removal, the signal is then pass through a Fast Fourier Transform (FFT) to convert the signal from the time domain back to the frequency domain. Thereafter, the signal goes through the demodulation process, a parallel to serial converter and finally the original signal is obtained. OFDM resources available in the time domain are referred to as symbols and in the frequency domain they are referred to as sub-carriers [5].

2.4.2 OFDMA Basics

OFDMA is a multiple-access and multiplexing technique that offers multiplexing operation for the data-streams of users through the use of downlink sub-channels and uplink multiple access by means uplink sub-channels [5], [39]. OFDMA differs from OFDM to the degree that it organizes the time (i.e. symbols) and the frequency (i.e. sub-carriers) resources into sub-channels for allocation to different users which permits for multiple access. Thus it can be said that OFDMA operates in two dimensions: frequency and time [40]. The symbol structure of the OFDMA as depicted in Figure 2.3, consists of three types of sub-carriers namely:

- **Data Sub-carriers:** They are used for the transmission of data [5].
- **Pilot Sub-carriers:** Used for channel estimation and for synchronization purposes [5].
- **Null Sub-carriers:** These are used as guard bands and DC (Direct Current) Subcarriers [5]. The DC subcarrier is the subcarrier whose frequency is equal the centre frequency of the transmitted radio frequency (RF).

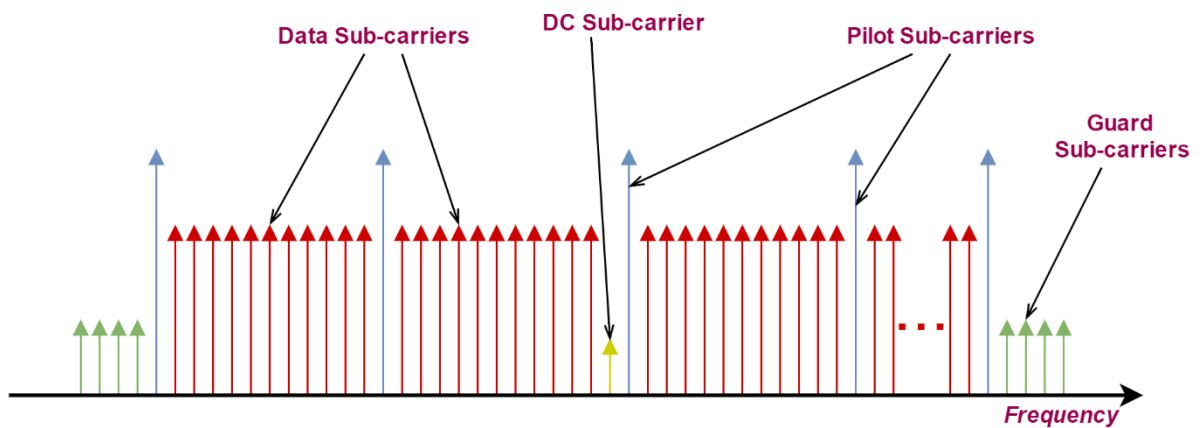


Figure 2.3 Structure of OFDMA Sub-carriers [5].

2.4.3 OFDMA Sub-Channelization

OFDMA sub-channelization involves the grouping of active data and pilot subcarriers into groups called sub-channels. These sub-channels are then dynamically allocated to subscribers based on channel conditions and data requirements. Sub-channelization is supported by the

WiMAX OFDMA-PHY both in the uplink and downlink. There are basically two types of arrangements/permutations for sub-channelization:

- **Diversity/distributed allocation:** The diversity/distributed allocation permutation, pseudo-randomly distributes the sub-carriers across the available bandwidth as well as arranges them to form sub-channels [41]. It provides frequency diversity especially in frequency selective-fading channels and inter-cell interference averaging [5]. It is also well suited for mobile communication.
- **Contiguous/adjacent allocation:** The contiguous/adjacent allocation permutation includes the DL FUSC (fully used sub-channelization), DL PUSC (Partially used sub-channelization) and UL PUSC some optional permutations. The contiguous/adjacent allocation permutation is used for non-selective and slowly fading channels and is also used for implementing adaptive modulation and coding (AMC).

It is also important to note that the minimum time-frequency resource allocation unit of sub-channelization is one *slot*, which is equal to 48 sub-carriers. In this thesis, the focus will be more on PUSC sub-channelization since it is mandatory for all WiMAX mobile implementation.

2.4.3.1 Partially Used Sub-Channelization (PUSC) Permutation Scheme

In the PUSC permutation scheme, WiMAX subscribers are allocated variable number of *slots* in the downlink and uplink directions. The actual definition of a slot depends on the sub-channelization method and the direction of transmission (i.e. UL and DL) [42], [43]. This section discuss the PUSC variations which consist of the DL-PUSC and UL-PUSC.

2.4.3.1.1 Downlink PUSC

In the DL-PUSC all the subcarriers are first of all arranged into six groups as shown in Table 2.2. The permutation of subcarriers to form sub-channels is done independently within each group, therefore ensuring a logical separation of one group from another. In all PUSC

variations, at the initial stage of sub-channelization, all the subcarriers except the null subcarriers are arranged into clusters [30].

Table 2.2 DL-PUSC Sub-carrier Permutation Parameters [30].

Parameters	Values			
FFT Size	128	512	1024	2048
Sub-carriers per cluster	14	14	14	14
Number of Sub-channels	3	15	30	60
Data Sub-carriers used	72	360	720	1440
Pilot Subcarriers	12	60	120	240
Left-guard Subcarriers	22	46	92	184
Right-guard Subcarriers	21	45	91	183
DC Sub-carrier	1	1	1	1

A cluster consists of 14 contiguous subcarriers over two OFDM symbols as shown in Figure 2.4. In each cluster (consisting of 28 subcarriers), the subcarriers are divided into 24 data subcarriers and 4 pilot subcarriers. After the formation of the clusters, they are then renumbered using a pseudorandom numbering scheme for the purpose of redistributing the logical identity of the clusters. On completion of the renumbering process, the clusters are separated into six groups, with the first one-sixth of the cluster belonging to group 0, and so on and so forth. A sub-channel is formed by combining two clusters from the same group as also illustrated in Figure 2.4.

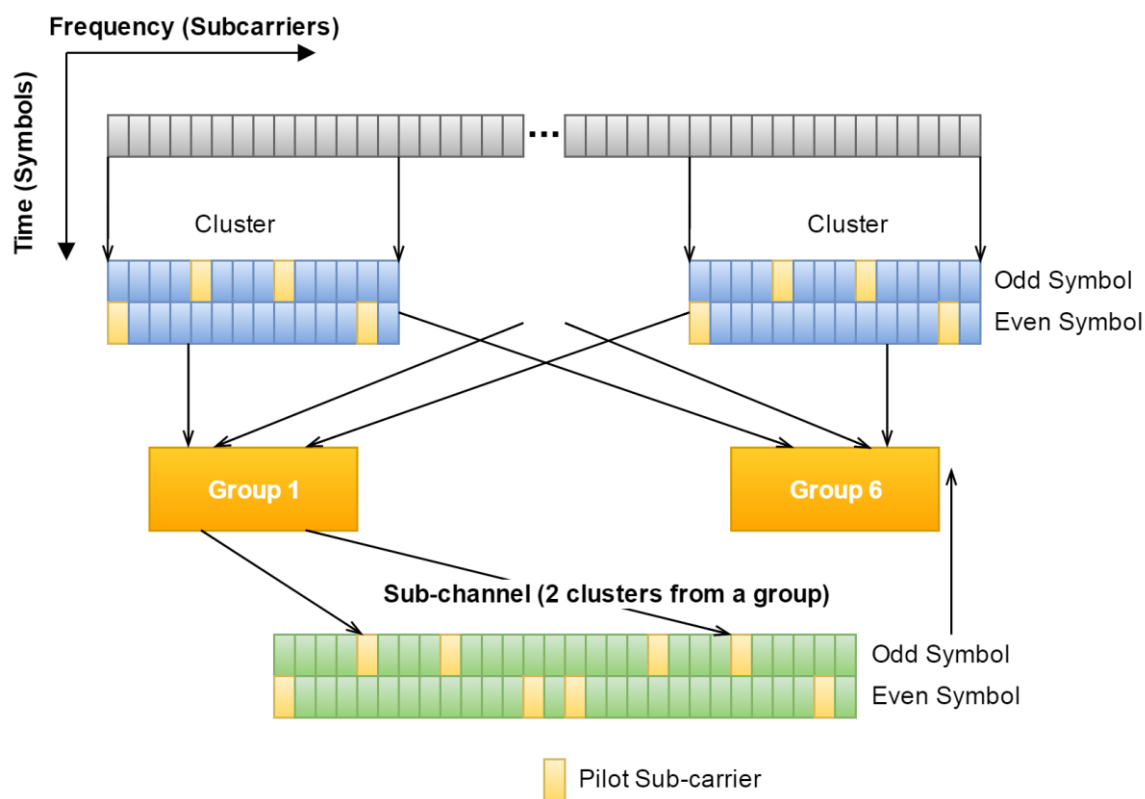


Figure 2.4 DL-PUSC Subcarrier Permutation [30].

In the PUSC sub-channelization scheme, it is possible to allocate all or a portion of the six groups to a particular transmitter. The act of apportioning disjoint subsets of the six available groups to neighbouring transmitters makes it possible to separate their signal in the subcarrier space thereby enabling tighter frequency reuse while trading-off data rate. Frequency reuse is a cellular concept whereby frequency resources assigned to a cell is reassigned to different cells repeatedly such that the cells are separated from each other by a large enough distance to keep radio interference levels within tolerable limits [44]. Using subcarriers in such a manner is referred to as *segmentation*.

Through the use of the segmentation scheme, all the sectors in a WiMAX base-station can use the same RF channel while their orthogonality between subcarriers is maintained. It is necessary to note that, although segmentation can be used with PUSC, PUSC by itself does not demand segmentation [30].

2.4.3.1.2 Uplink PUSC

In the permutation of UL-PUSC, the subcarriers are first of all divided into various portions known as *tiles*. A tile consists of four sub-carriers over three OFDM symbols. The subcarriers contained in a tile are divided into eight data subcarriers and four pilot subcarriers as shown in Figure 2.5 below:

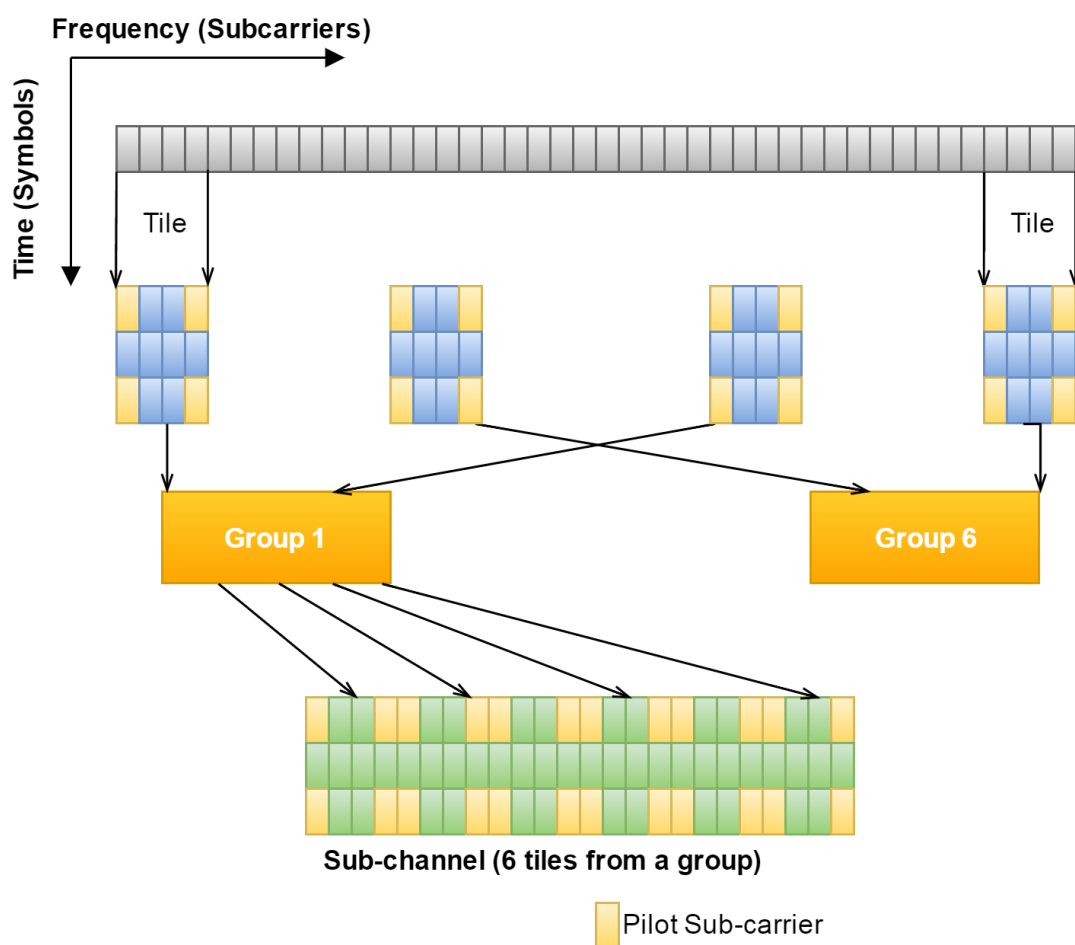


Figure 2.5 UL-PUSC Subcarrier Permutation [30].

There is an alternative UL-PUSC mode whereby each tile consists of three subcarriers over three OFDM symbols. In this particular scenario, the data subcarriers of a tile are divided into eight data subcarriers and one pilot subcarrier. The optional UL-PUSC has lesser ratio of pilot subcarriers to data subcarriers and this ensures a higher data rate but diminished channel

tracking capability. After the tiles are created, they are then renumbered by using a pseudorandom numbering sequence thereafter they are distributed into six groups. Every individual sub-channel is created by using six tiles from a single group. The UL-PUSC can be used with segmentation to enable the system operate under constricted frequency re-use patterns [30].

2.4.4 Scalable OFDMA

Mobile WiMAX (IEEE 802.16e) is designed based on the idea of scalable OFDMA (S-OFDMA). S-OFDMA provides additional benefits over OFDMA as it supports a wide range of channel bandwidths which allows it to flexibly allocate spectrum to meet with varied demands. The scalability of S-OFDMA is made possible by adjusting the FFT size and at the same time fixing the subcarrier frequency spacing at 10.94 kHz. As a result of the resource unit subcarrier bandwidth and symbol duration being fixed, the impact to the higher layers (parameters) is minimal when the bandwidth is scaled. The Table 2.3 describes the S-OFDMA parameters.

Table 2.3 S-OFDMA Parameters.

Parameters	Values			
System Channel Bandwidth (MHz)	1.25	5	10	20
Sampling Frequency (F_p in MHz)	1.4	5.6	11.2	22.4
FFT Size	128	512	1024	2048
No. of Sub-channels	2	8	16	32
Subcarrier Spacing	10.94 kHz			
Useful Symbol Time ($T_b = 1/f$)	91.4 μ s			
Guard Time ($T_g = T_b/8$)	11.4 μ s			
OFDMA Symbol Duration ($T_s = T_b + T_g$)	102.9 μ s			
No. of OFDMA Symbols (5ms/Frame)	48			

2.4.5 Mobile WiMAX Frame Structure

The physical layer of WiMAX IEEE802.16e standard supports the use of duplexing techniques such as—Time Division Duplexing (TDD), Frequency Division Duplexing (FDD) and half-duplex FDD (H-FDD). In the case of FDD, the uplink and downlink subframes are simultaneously transmitted on separate carrier frequencies; while for TDD, the uplink and downlink subframes are transmitted on the same carrier frequency but at different times. H-FDD is a basic FDD duplexing scheme restricted for use by the Mobile Station (MS). This is to ensure that the MS cannot transmit and receive at the same time. In terms of general application of Mobile WiMAX, TDD is the preferred duplexing mode and it is so for the following reasons:

- It allows flexible adjustment of the uplink/downlink ration to cater for asymmetric uplink/downlink traffic whereas FDD is always has fixed and equal DL and UL bandwidths [5].
- While FDD requires a pair of channels, TDD requires only a single channel for both DL and UL providing greater flexibility and adaptation for different spectrum allocations.
- TDD makes sure that there is channel exchange for the support of link adaptation, MIMO and other advanced antenna technologies.
- TDD transceiver design and implementation are less complex and consequently less expensive as compared with FDD.

The Figure 2.6 provides an illustration for the WiMAX TDD OFDMA frame. The frame is divided into the DL and UL subframes which are separated the Transmit/Receive Transition gap (TTG) and Receive/Transmit transition gap (RTG) to avoid transmission collisions. The UL and DL subframes contain control information to ensure optimal operation of the system and they include:

- **Preamble:** This is the first symbol of the frame and it is situated at the DL sub-frame. It is used for physical layer procedures, such as, time-frequency synchronization and initial channel estimation.

- **Frame Control Header (FCH):** It follows after the preamble and it provides frame configuration information such as medium access protocol (MAP) message length, the modulation & coding scheme and the usable subcarriers.
- **DL-MAP and UL-MAP:** The UL-MAP and DL-MAP messages specify the allocation data regions (Burst) within the frame to multiple users. These messages are broadcasted after FCH in the DL sub-frame.
- **UL Ranging:** The uplink ranging sub-channel is reserved for the MS to perform bandwidth requests, closed-loop frequency-time and power adjustments.
- **UL Channel Quality Indication Channel (CQICH):** This is allocated to the MS for feedback channel state information.
- **UL Acknowledgement (ACK):** This is allocated to the MS in order to receive downlink feedback acknowledgements [5], [30].

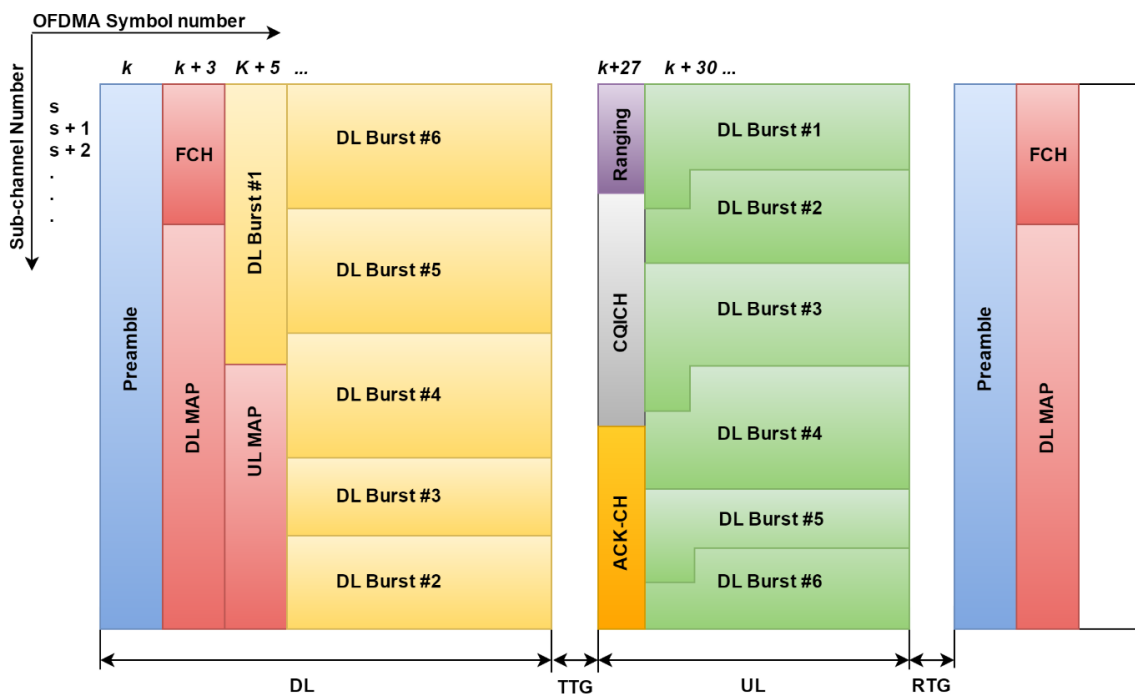


Figure 2.6 Frame Structure for WiMAX OFDMA.

2.5 Mobile WiMAX MAC-Layer

Having described the PHY layer of mobile WiMAX in Section 2.4, this section discusses in details the Medium Access Control (MAC) layer and its basic functions and operations; dwelling particularly more on the areas that relates to this research. The MAC layer resides just above the PHY layer—the PHY layer is also referred to as layer 1 in the Open System Interconnect (OSI) stack. The major function of the WiMAX MAC layer is to act as an intermediary or to provide an interface between the higher layers (transport layer and above) and the physical layer. The MAC layer receives packets from the upper layer and converts these packers into MAC service data units (MSDUs). The MSDUs are organized into MAC protocol data units (MPDUs) before transmission over the air interface. A reverse action is done when the MPDUs are received by the mobile stations. The WiMAX MAC uses a variable-length MPDU to allow flexibility in the variation of messages being sent and it also ensures efficiency in transmission [30]. In a more granular perspective, the WiMAX MAC layer is subdivided into three layers namely: the convergence sublayer (CS), the common-part sublayer and the security sublayer as shown in Figure 2.7 below:

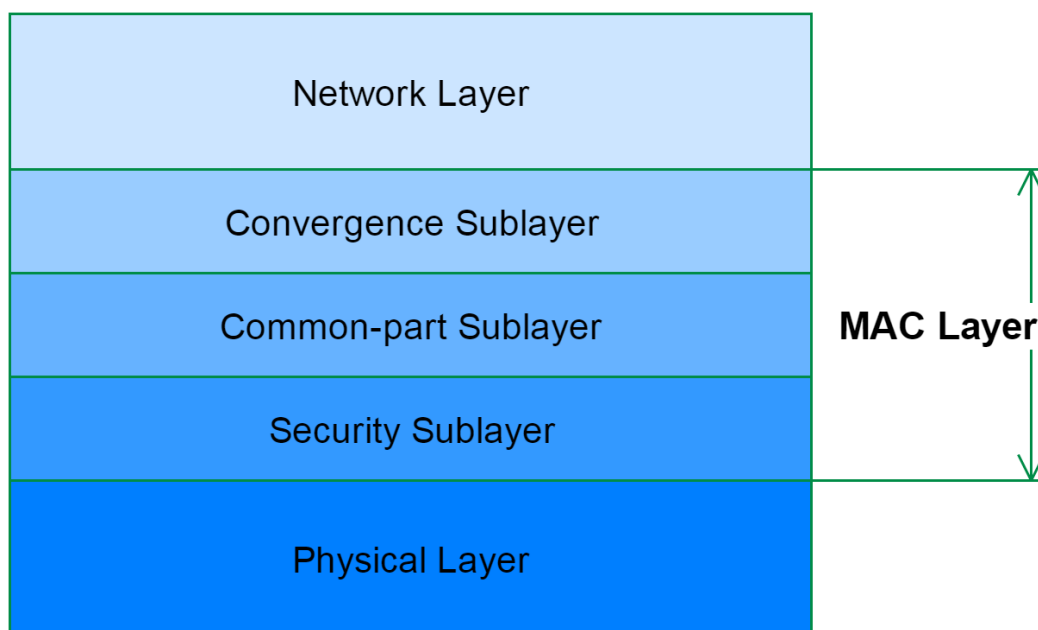


Figure 2.7 WiMAX Protocol Stack.

The CS is the portion of the MAC that interfaces with the higher layers. Its primary functions includes the compression of higher layer headers and address mapping. The common-part sublayer carries out all the packet operation independent of the higher layers, for instance: fragmentation, formation and transmission of MPDUs, QoS control and Automatic Retransmission Request (ARQ). ARQ is a WiMAX feature that requires every transmitted packet to be acknowledged by the receiver. Unacknowledged packets are presumed to be lost and therefore will have to be retransmitted. Finally the security sublayer provides encryption, user authentication and reliable exchange of encryption keys between the base-station and mobile stations [30], [45], [46].

2.5.1 Channel Access Method

In WiMAX, the base-station bears the responsibility of allocating bandwidth to all users both in the uplink and downlink directions. The WiMAX standard provides mechanisms that enables an MS to obtain uplink bandwidth based on the QoS and traffic parameters needed for a particular service. The base-station periodically allocates dedicated channels to each MS in its cell, which the mobile stations use to request for bandwidths. This process is referred to as *polling*. The Polling Process could be done individually (unicast) or performed in groups (multicast).

The multicast polling is usually done when bandwidth is insufficient for individual polling. In this case, the allocated channel or slot for making bandwidth request is shared between the mobile stations in the multicast group, causing contention for access amongst the mobile stations. The WiMAX standard defines a contention access and resolution mechanism in a situation where multiple mobile stations attempt to use the shared slot. Details of this contention resolution mechanism is extensively described in [40], [47].

2.5.2 WiMAX Quality of Service

The key and major function of the WIMAX MAC layer is to guarantee that the QoS requirements for all the MAC PDUs belonging to different service flows are reliably met. Some of the ideas behind the WiMAX MAC design is gotten from the Data-Over-Cable Service

Interface Specifications (DOCSIS) cable modem standard [48]. The MAC architecture is based on a connection-oriented architecture, whereby every downlink and uplink connection is managed by the serving base-station. For any data transmission to occur between a base-station and a mobile station, there must exist a unidirectional link logical link between them and this link is called *connection*.

The *connection* for every single MAC-layer peer in WiMAX is identified by a connection ID (CID). The CID serves as a temporary address for data transmission for every single MAC-layer peered link. In addition, WiMAX also defines a connection conception known as a *service flow*. A *service flow* can be defined as a unidirectional flow of packets containing a particular set of QoS parameters and possessing a unique identifier known as a *service flow identifier* (SFID).

WiMAX QoS parameters are most likely to include—traffic priority, maximum sustained traffic, maximum delay, minimum reserved rate, tolerated jitter, type of scheduling etc. Service flows are usually created through the network management system and the base-station is responsible for issuing SFID and mapping it to unique CIDs [30]. The service flow QoS mechanism is applicable to the UL and DL direction to ensure that there is improved QoS in both directions. The WiMAX standard defines five categories to support a broad range of applications as defined in Table 2.4.

WiMAX MAC also delivers scheduling services that ensures efficient delivery of broadband data services (voice and multimedia) over a time varying broadband channel. Some of the properties of the WiMAX MAC scheduler services comprises of a fast data scheduler that ensures efficient allocation of available resources to bursty data traffic with time varying channel conditions, it schedules both in the UL and DL directions; it supports dynamic resource allocation whereby the allocation is delivered in MAP messages both in the UL and DL; it is QoS oriented and finally, it performs frequency selective scheduling by which the scheduler can operate on different types of sub-channels [5].

Table 2.4 WiMAX QoS Classification.

QoS Category	Application Examples	QoS Parameters
Unsolicited grant services (UGS)	Voice over IP (VoIP)	Minimum Reserved Rate Maximum Sustained Rate Maximum latency tolerance Jitter tolerance
Real-time Polling service (rtPS)	Streaming audio and video, MPEG (Motion Picture Experts Group) encoded	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Traffic priority
Non-real-time Polling service (nrtPS)	File Transfer Protocol (FTP)	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency tolerance Jitter Tolerance Traffic Priority
Best-effort service (BE)	Web browsing, data transfer	Maximum sustained rate Traffic priority
Extended real-time Polling service (ErtPS)	VoIP with silence suppression	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Jitter tolerance Traffic priority

2.6 Chapter Relevance

It is important to note at this juncture that this chapter provides a theoretical background to WiMAX's spectrum design, which is very key area to the literature review of this thesis. It was written in an educational style, in order to provide detailed information about the MAC and PHY layer design for WiMAX, particularly, mobile WiMAX. Amongst the topics discussed includes: the WiMAX OFDMA sub-channelization mechanism which describes how WiMAX's OFDM subcarriers are arranged into sub-channels in the WiMAX spectrum; S-OFDMA parameters which are a unique features of mobile WiMAX showing how the WiMAX spectrum/bandwidth is scaled from 1.25MHz to 20MHz as well as their corresponding FFT sizes (Table 2.3); the WiMAX frame structure and the WiMAX QoS parameters. These subject areas are fundamental in the design process of WiMAX spectrum virtualization and network federation as described in Chapters 3, 4 & 5. WiMAX spectrum features such as FFT size,

frame duration, sub-channelization methods (DL PUSC) and bandwidth size constitute part of the simulation parameters configured in the various experiment scenarios carried out in this research.

2.7 Summary

In this Chapter, the WiMAX standard development and evolution was discussed, stressing the role of the WiMAX forum in harmonizing all its various standards. The PHY layer was also explained expressing the underlining importance of the OFDM and OFDMA in the arrangement of its time-frequency spectral resources as well as the importance of sub-channelization schemes such as the PUSC which are very vital in the virtualization of the WiMAX spectrum. Also the function of the WiMAX MAC as regards acting as an intermediary between the upper protocol layers and the PHY layer was discussed and its ability to create dedicated service flow channels between a BS and MS with guaranteed QoS. The guaranteed mobile WiMAX QoS definitions for various traffic types are important to understand, with regards to how spectrum is allocated by WiMAX base-stations for each traffic service. This relationship between QoS traffic definitions and WiMAX base-station spectrum allocation to its subscribers/mobile stations is expressed in the result analysis of the experiments carried out in chapter 4 & 5 of this thesis.

Chapter 3 WiMAX Virtual Spectrum Simulation

Plan Design

The goal of this Chapter is to provide a thorough and in-depth description of the simulation tool and design model used for the WiMAX spectrum virtualization. The OPNET Modeler now referred to as the Riverbed Modeler [49] was used in carrying out all the network modelling, simulation and statistical analysis done in this research. This Chapter explains the modular structure of the OPNET Modeler, the OPNET WiMAX modular design and the VS-Hypervisor's OPNET modular design Implementation. Regardless of the name change of the OPNET Modeler to Riverbed Modeler, within the context of this thesis, the former name will still be used.

3.1 Introduction to OPNET Modeler

The Optimized Network Engineering Tools (OPNET) Modeler was formerly owned and created by OPNET Technologies Inc., before it was acquired by Riverbed Technology in 2012 [49]. The OPNET Modeler is one of the foremost commercial products that provides network modelling and simulation software solution and it is extensively used by researchers, engineers and university students. It is a highly dynamic discrete event simulator (DES) with an easy to use graphical user interface (GUI) and it supports hybrid simulation, analytical simulation and 32-bit/64-bit fully parallel simulation [50]. It is a mathematical or logical model of a physical system that comprises of changes at specific points in simulated time [51].

The OPNET Modeler provides an extensive development environment with a full set of tools including a model design, simulation, data collection, data analysis and it supports the modelling of communication networks such as WiMAX and distributed systems.

3.2 The OPNET Environment

As stated earlier, the OPNET Modeler offers a highly comprehensive development environment with lots of modelling features, but for context of this research, emphasis will only be paid on the OPNET Modeler Editors.

3.2.1 OPNET Modeler Editors

In the OPNET Modeler, there exists quite a number of editors that simplify the modelling and simulation task and they come with graphical user interface (GUI) features. For the purpose of this thesis, only the editors that were used for this research work will be discussed and that includes: the Project Editor, Node Editor, Process Editor and open model source code. These editors are hierarchical in OPNET as illustrated in Figure 3.1 below:

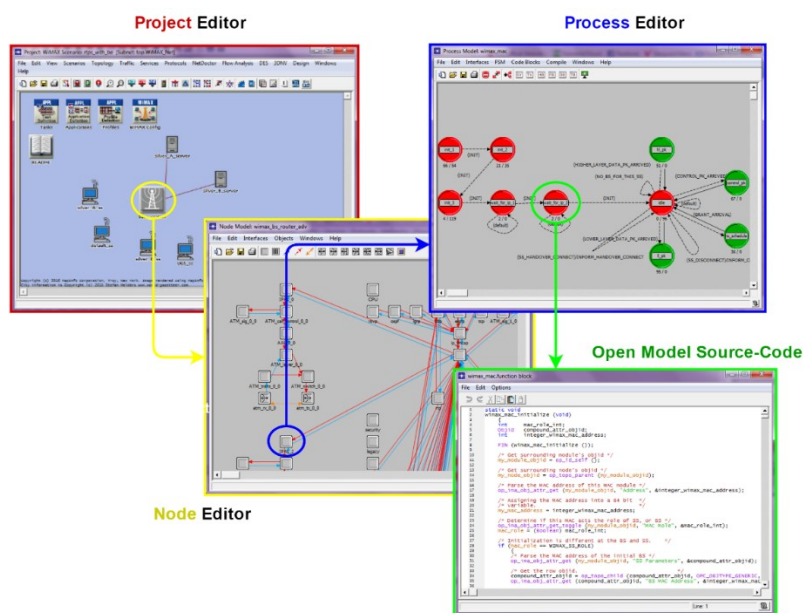


Figure 3.1 Hierarchical OPNET Editors.

Each of the editors enables the user to do some set of related functions within a window that is contained in the general graphical environment of OPNET. Table 3.1 provides more details on each of the hierarchical editors [52].

Table 3.1 Purpose of the Hierarchical OPNET Editor [52].

Editor	Purpose
Project Editor	The Project Editor serves the purpose of editing the topology of a communication network model. It also used for basic simulation and analysis.
Node Editor	It is used in specifying the arrangement of device models. These device models can be represented as node objects in the Network Domain (such as computer work-stations, packet switches, and bridges).
Process Editor	The Process Editor is used in specifying the activities of the process models. Process models are represented as processes in the Node Domain and exist inside the processor, queue, and external system modules. The Process models make use of the finite state machine (FSM) paradigm to express actions that are subject to current state and new stimuli.

3.3 Overview of OPNET WiMAX Model Suite

This section discusses the OPNET WiMAX model suite and its basic features. The OPNET WiMAX suite is based on the mobile WiMAX IEEE802.16e standard. The suite includes a discrete event simulator that permits the analysis of network performance in a wireless metropolitan area network. It is necessary to note that the WiMAX suite comes with a license that permits the viewing or the modification of WiMAX process models. The following subsections are discussions on some of the important features of the OPNET WiMAX Model suite.

3.3.1 Model Features

The OPNET WiMAX Model features a variety of important functionalities as specified in the IEEE802.16e standard. It includes MAC messages such as bandwidth requests and MAC PDU. It possess a radio link control for static burst configuration for every BS and MS connection. Scheduling and QoS categories UGS, ertPS, rtPS, nrtPS and BE are supported as well as QoS

service flows. A summary of the aforementioned features along with other features is summarized in Table 3.2 below.

Table 3.2 OPNET WiMAX Features.

Model Feature	Description
MAC Messages	802.16e MAC PDU, 802.16e management messages (bandwidth requests and MAPs), ARQ messages, Mobility messages and Ranging messages.
Radio link control	Allows configuration of static burst profile for each connection
Mobility	The ensuing mobility features are modelled: Dynamic selection, Neighbour advertisements of predefined scanning, mobile subscriber or base station scanning.
Scheduling service	Supports UGS, ertPS, rtPS, nrtPS and BE
Packet loss modelling	This feature models packet losses caused by physical layer effects.
Bandwidth allocation and request mechanisms	Aggregated requests, Piggybacked bandwidth requests.
PHY modelling	Models the PHY-layer overheads along with the PHY profiles for OFDM, OFDMA, and SC. It models co-channel interference for OFDMA and SC. It also path-loss for OFDMA and SC
Broadcast and multicast traffic	The model supports broadcast and multicast traffic when physical layer modelling is enabled.
Quality of service (QoS)	The QoS features supported are as follows: Admitted and active Service flows , Service class name parameters, Dynamic service flow creation, Global service class name, global service flows and Per-connection queuing/buffering.
Initial SS and BS association	Ability to specify which base station a subscriber station is connected.

3.3.2 OPNET WiMAX Model Structure

This section describes the three major underlying OPNET WiMAX model structure components which are the Network, Node and Process models.

3.3.2.1 Project Model

The WiMAX network model or any network model is created within the project editor in OPNET. This environment provides the platform and tool-box of setting-up and modelling any network architecture. It possess drag and drop features for adding network objects such as switches, servers, base-stations, subscriber (SS) workstations, links etc. from an object palette that allows for the formation of networks. The Figure 3.2 below provides an example illustration of a modelled WiMAX network [52].

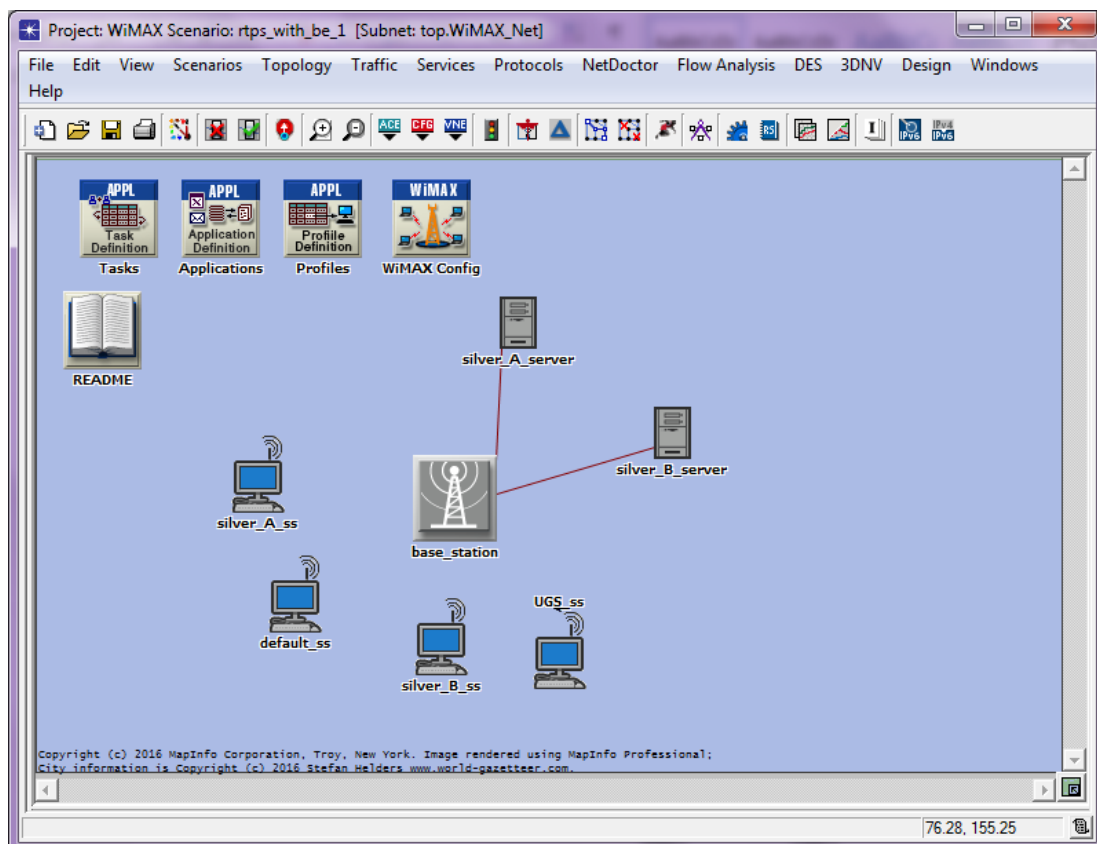


Figure 3.2 A WiMAX Network model in OPNET Project Editor.

3.3.2.2 Node Model

The node model in OPNET is a blocked-structured approach used in representing the internal functionalities of a network node object. The blocks, which are interconnected within a node model are referred to as *modules*. Each module comprises of a set of inputs and outputs and some state memory. Node models determine the manner in which the inputs and outputs of various modules are connected using objects which are called *connections*.

There are basically two types of connection, one that carries data packets and the other that conveys individual values e.g. statistical values. The node model structure shown in Figure 3.3 is that of a WiMAX subscriber workstation. It represents the predefined protocols based on the IEEE802.16e standard. These protocols includes the application layer, TCP/IP, UDP, ARP, MAC and PHY. It also models transceiver antenna for the subscriber station [49].

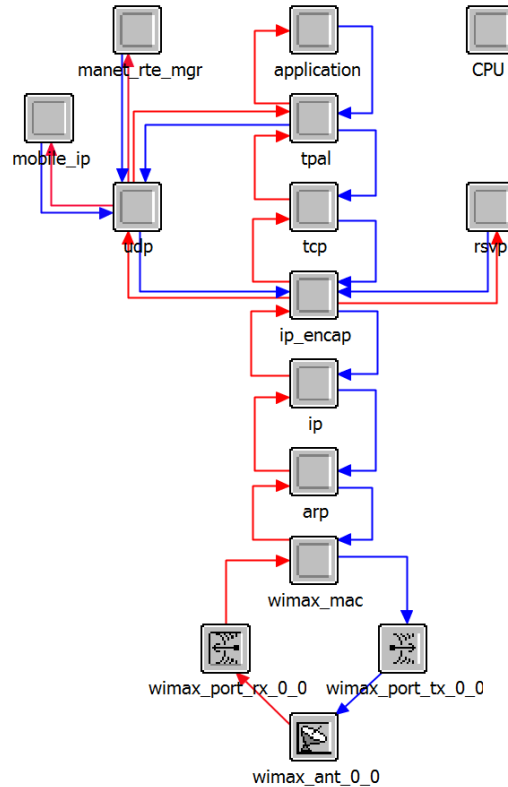


Figure 3.3 WiMAX Subscriber Station Node Model [52]

The OPNET WiMAX Model provides a separate node model structure for the WiMAX base-station; different from that of the subscriber station previously described and this is illustrated in Figure 3.4. In general, the OPNET WiMAX Model consists of a suite of various node models and they include: subscriber station (SS) node models, base-station node models, servers and configuration nodes. A summary of the WiMAX node models used in this research is shown in the Table 3.3 below:

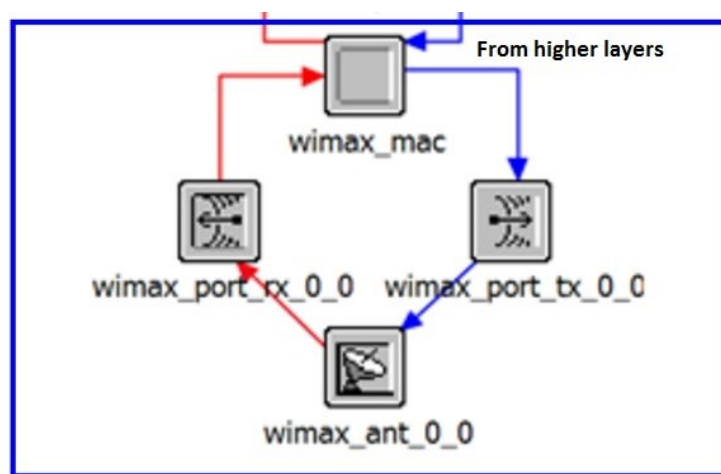


Figure 3.4 OPNET's WiMAX Base-Station MAC Node Model [49]

Table 3.3 WiMAX Node Models in OPNET

Node Model	Description
wimax_bs_ethernet4_slip4_router	Functions as a Fixed base station node model with a router. This node has four Ethernet interfaces, four SLIP interfaces, and one WiMAX interface.
wimax_ss_server	Mobile subscriber station node model with server functionality.
wimax_ss_workstation	Mobile subscriber station node model with workstation functionality.
WiMAX_Config	The Global configuration object is used to configure base-station and subscriber station parameters such as PHY profiles and service classes.


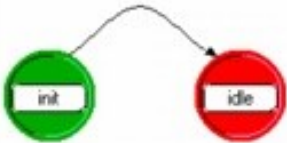
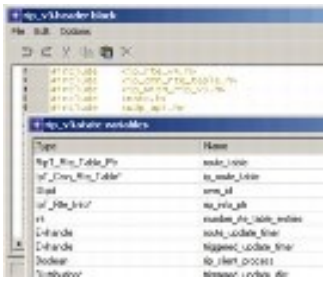
3.3.2.3 OPNET Process Models

OPNET's process Models are created and edited in the Process Editor. They are used to express the behaviour of the *modules* inside a node model. Process models are also used to model and setup an extensive range of hardware and software subsystems such as: algorithms, communication protocols, operating systems, shared resources, custom statistics etc. In developing these subsystems and to properly define them, OPNET uses only one programming language, called *Proto-C*. Proto-C is supported by the process editor and it is fully incorporated in the OPNET Modeler application. The Proto-C programming language is a powerful language that incorporates the capabilities of the C/C++ programming languages [52].

As aforementioned, the finite state machines (FSM) which are used in the describing the behaviour of process models are actually state transition diagrams (STD). *States* are used generally in representing top-level modes that a process can enter, while *transitions* specify the changes in state that are possible for the process. Both state and transitions are components of Proto-C and STDs. They are represented graphically in the process editor. The objects used in building process models are listed in Table 3.4.

It is necessary to note that while the STD represents the process models graphically, the Proto C programming language used by OPNET supports the textual representation of all parts of a process model. This textual representation is performed inside the state and transition objects and it is established on a robust library of simulation distributed-system related procedures or OPNET's unique application program interfaces (APIs). The diagram and logic of the Proto-C programming language can easily be converted into the C and C++ languages with nominal overhead, permitting them to perform efficiently. Principally, state information access, and control-flow statements (for instance, selection structure statements like *if-else* statements and iteration statements that sequence through multiple operations) are implemented in a direct manner to ward off any loss of performance.

Table 3.4 Process Model Objects [52]

Object Type	Definition	Representation
State	It characterises a mode of the process which has been achieved as a result of preceding stimuli and analogous decisions. States comprise of code conveying processing that is done soon after they are entered, or immediately before being exited.	
Transition	Specifies a likely path that a process can take from a source state to a destination state. Every state could be the source and destination of any number of transitions. A transition has a condition statement which stipulates the prerequisites for the process to occur after the transition.	
Model Level Information Blocks	There are quite a few blocks of text that specify additional components of the process and they include: declaration of state, and temporary variables; user-defined functions that can be called by the process' states and transitions; code to be implemented upon the termination of a process; and the declaration of global variables, data structures, etc.	

3.3.2.4 Force and Unforced States

OPNET process model states exists in two kinds of states called *forced* and *unforced* and they have varying execution times. In Proto-C illustrations, forced states are graphically symbolised as green circles and the unforced are represented as red circles as shown in the Figure 3.5 below:



Figure 3.5 Graphical Representation of Forced and Unforced States [52].

Unforced states allow pauses in-between state execution. Therefore it can be used to measure the true state of a system. As for forced states, there is no waiting period during process execution and thus cannot be used to represent modes of a system that persist for a given duration.

3.3.2.5 WiMAX Process Models

The OPNET Modeler defines three basic process models (*wimax_mac*, *wimax_bs_control* & *wimax_ss_control*). The *wimax_mac* and *wimax_bs_control* are the most crucial in this research, for they are central in the direct control of the base-station. They are shown in Figure 3.6. The *wimax_bs_control* and *wimax_ss_control* are child-processes of the *wimax_mac* and they are accessed by *right-clicking* anywhere on the *wimax_mac* process model. A detailed explanation of these three process models aforementioned are described in Table 3.5.

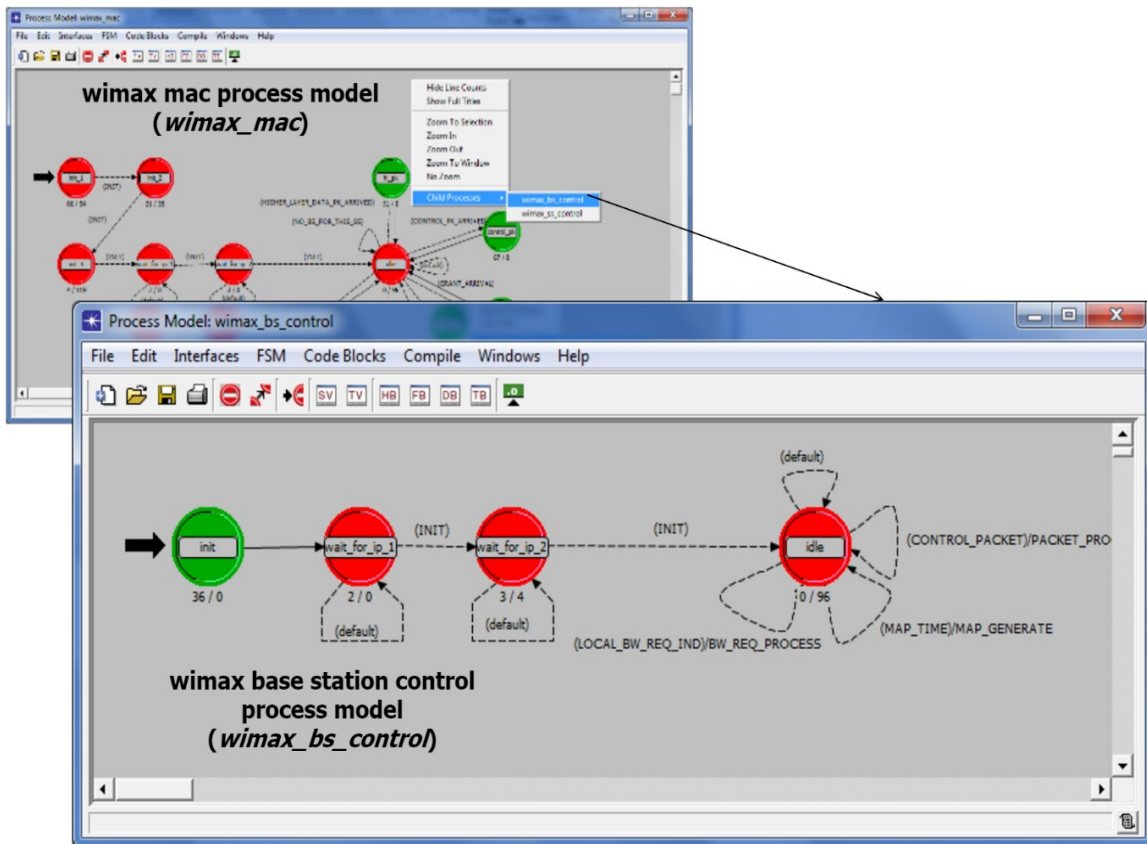


Figure 3.6 OPNET WiMAX MAC and Base-station Control Process Models.

Table 3.5 WiMAX Process Models Description [52].

Process	Description
wimax_mac	<p>This is the core process for WiMAX functionality and it is in charge of the data plane control (MAC layer), which includes the following: the forwarding of data, Categorizing higher-layer traffic to service flows, higher-layer packets in MAC frames Encapsulation/Decapsulation, Bandwidth request/grant mechanism, ARQ and Packet delivery.</p> <p>Depending on if the interface is on a base-station or subscriber station, this process is the parent process of the <i>wimax_bs_control</i> (base stations) or <i>wimax_ss_control</i> (subscriber station) process.</p>
wimax_bs_control	<p>This is a child process of the <i>wimax_mac</i>. It performs WiMAX functionality on base stations, including: MAP generation, Admission control, Activating service flows admittance, Bandwidth grant scheduler, Sending neighbour advertisements, Commanding the SS to enter scanning mode, Releasing SS resources after handover and Responding to ranging messages.</p>
wimax_ss_control	<p>This is another child process of the <i>wimax_mac</i>. It implements WiMAX features on subscriber stations, including:</p> <ul style="list-style-type: none"> • Initiation of admission control • Service flows activation • MAP decoder • Initiation of SS handovers • It initiates scanning mode and the scanning of neighbouring base stations • Ranging (initial and periodic) • Serving base station selection

3.3.3 OPNET WiMAX Configuration Object

The general WiMAX model attributes are configured from a singular network node known as the object. The attributes that can be configured on this node object includes: Adaptive Modulation and Coding (AMC) Profile sets definition, contention parameters, efficiency mode, MAC service class definitions, OFDM & OFDMA PHY Profiles and Single Carrier (SC) PHY Profiles. The Figure 3.7 below provides an illustration of the configuration environment.

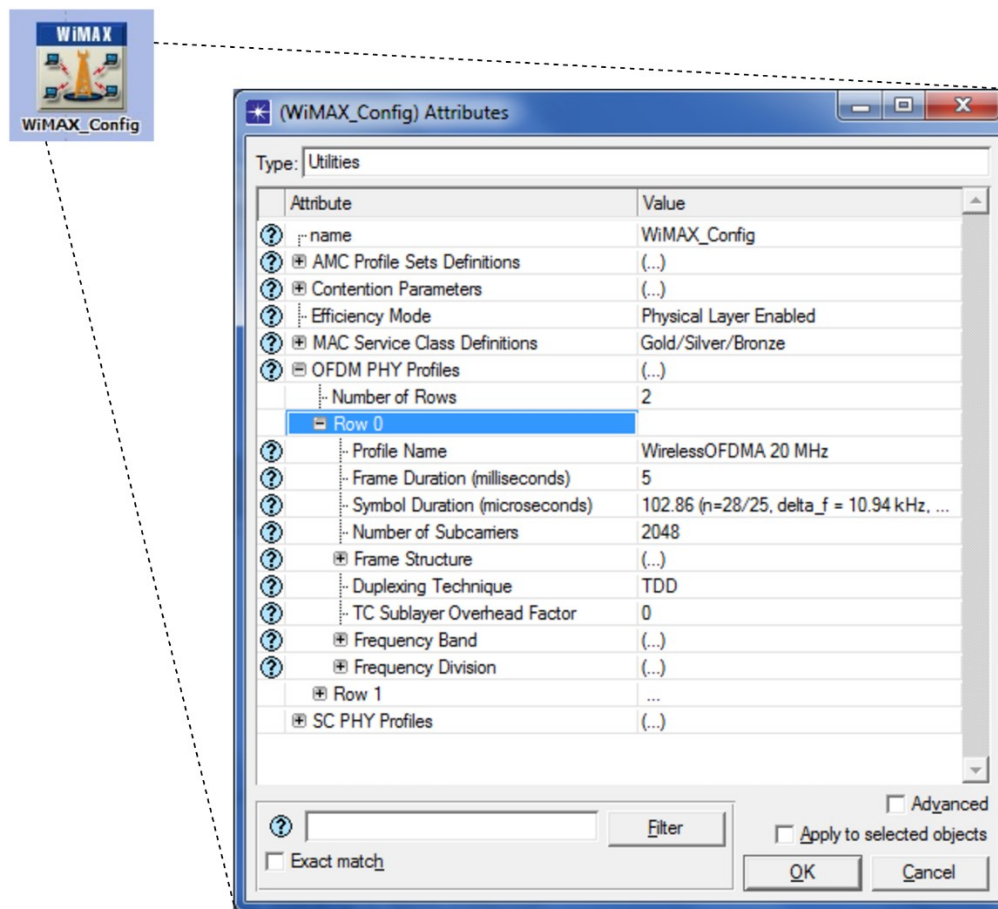


Figure 3.7 OPNET WiMAX Configuration Object.

3.3.4 OPNET Application Configuration Node

The application configuration node is a standard OPNET node used for the configuration of different application traffic such as HTTP, Video Conferencing, VoIP, Web Browsing etc. The traffic generated is what creates demand on the network bandwidth and the underlying network technology. The traffic is also what creates the load on the servers. After the applications are configured in OPNET, they are later used by the profile configuration to create unique user application profiles. For instance you can have a user profile whereby all the users in the profile are configured to use only the VoIP application. Figure 3.8 shows a sample window of OPNET configuration node with various application types.

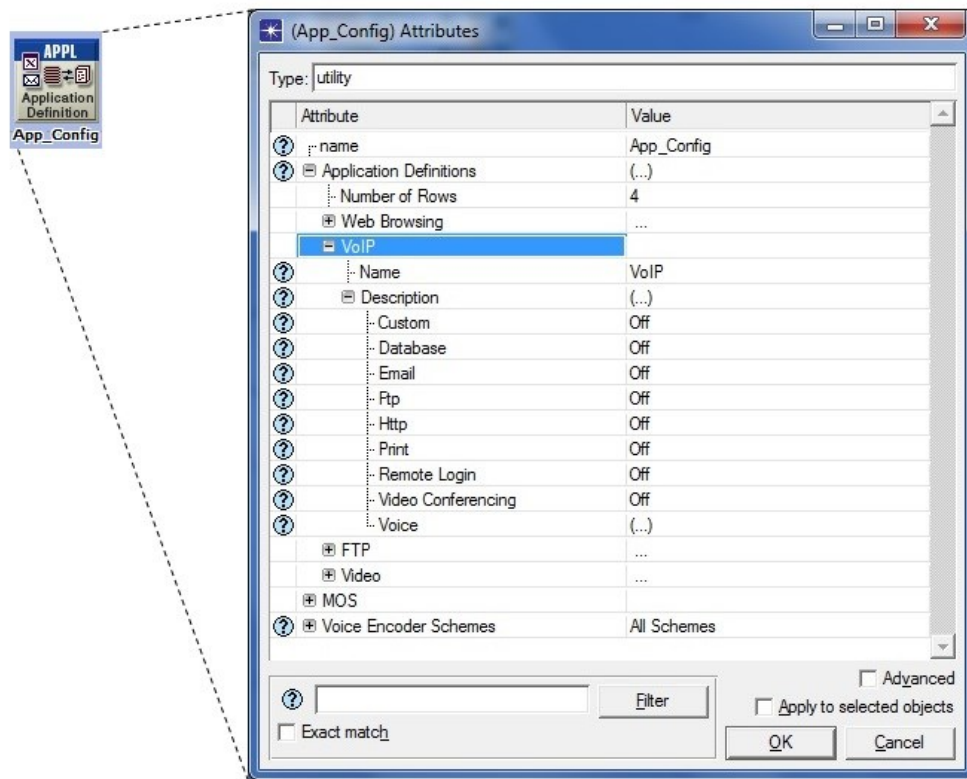


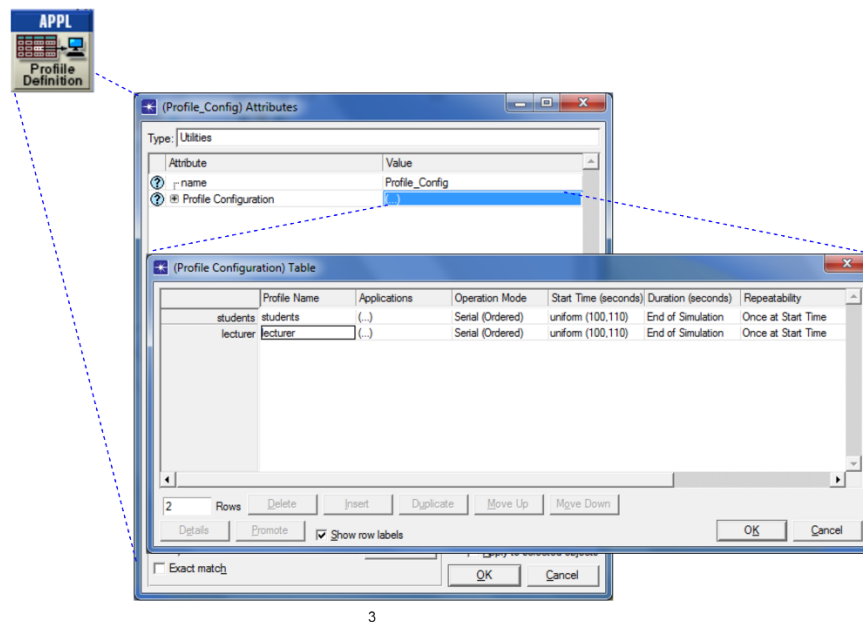
Figure 3.8 OPNET Application Configuration Node.

3.3.5 OPNET Profile Configuration

The OPNET profile configuration is used to configure and define the activity patterns of a user group based on the applications used over a period of time. Different user profiles can be created running on different user nodes/workstations. A profile contains a list of applications and OPNET makes it possible to configure the applications within a profile to able to perform in diverse ways relative to the operation mode of the application itself and they include:

- Being able to execute at the same time
- One after the other—in a specific order as defined by the researcher.
- One after the other—in a random order.

Figure 3.9 shows an example of two different profiles configured on the Profile Config node.



3

Figure 3.9 OPNET Profile Configuration.

3.4 Spectrum Virtualization Implementation on OPNET

This section describes and explains how the concept of spectrum virtualization is achieved in OPNET. The OFDM and OFDMA PHY attributes for the WiMAX base-stations and mobile stations in OPNET are set and configured by the *WiMAX Config* node and these attributes are stored in a network wide database/repository as shown in Figure 3.10. These attributes includes: frame duration, frame structure, duplexing technique (TDD/FDD), number of subcarriers, frequency bandwidth etc. To achieve spectrum virtualization, whereby all the virtual base-station share the same frequency resources, a novel entity denoted to as the *VS-Hypervisor*, previously stated in Section 1.2.3 bears the responsibility for the frequency resource sharing. The *VS-Hypervisor* is implemented in OPNET as an independent network node object possessing its own node and process model. The node model consists of a singular processor module and its process model comprises of its own STD.

Upon creation and storage of the PHY attributes by the WiMAX Config node via its process model, known as the *wimax_attr_definer* in the global data repository, the values are then grouped into PHY profiles, assigned and parsed to the *wimax_mac* process model. The

wimax_mac process model is contained in the WiMAX MAC module of both the virtual base-stations and the mobile stations and they both have a read-only privilege to the PHY attributes in the repository as shown in Figure 3.10.

It is important to note that the virtual base-stations were originally WiMAX physical base-stations in OPNET but they have been linked together to behave like one physical base-station by the *VS-Hypervisor* through the use of global header-files and external C-codes that have control over their individual MAC layers. The global header files and external c-codes are contained in the process models of the individual base-stations.

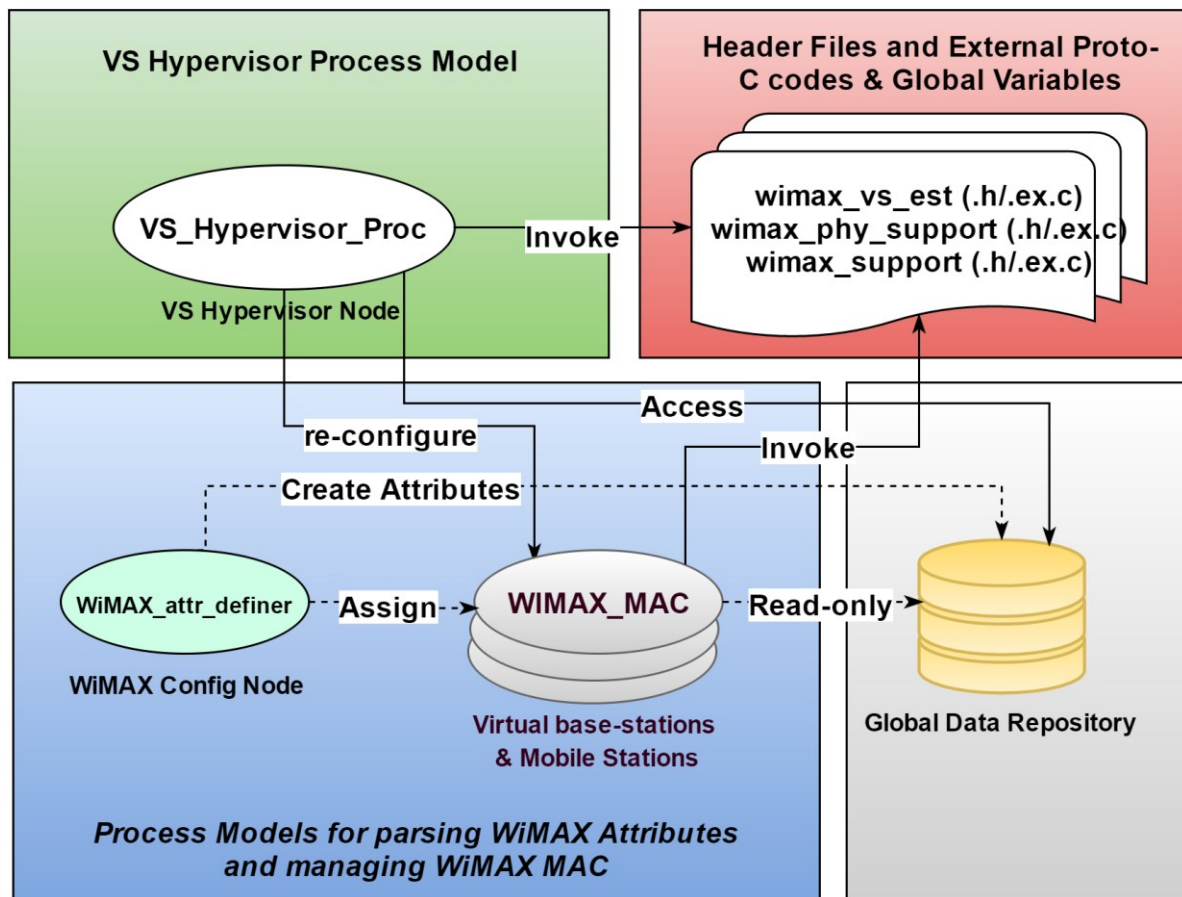


Figure 3.10 Spectrum Virtualization Implementation Reference Model in OPNET.

In order for the virtual base-stations and mobile stations to have full utilization and control of their PHY resources and also for better MAC control, OPNET provides unique headers files where global and external variables are declared as well as the declaration of specialized functions. The header files (.h) and external C-codes (.ex.c) necessary for manipulating and

handling PHY resources are known as the *wimax_support (.h/ex.c)* and *wimax_phy_support (.h/ex.c)*. These files can be invoked at any-time by the *wimax_mac* process model and its child processes (*wimax_bs_control* & *wimax_ss_control* mentioned in Section 3.3.2.5) residing in the virtual base-stations and mobile stations. To fully implement spectrum virtualization, the VS-Hypervisor requires access and the ability to invoke the *wimax_support (.h/ex.c)* and *wimax_phy_support (.h/ex.c)* header files and extern c-codes; hence these files are declared within its process model. Through its access to these files and to the global data repository, the *VS-hypervisor* is able to re-configure and re-allocate of PHY resources particularly spectrum resources for the virtual base-station and the virtual base-station subsequently allocates appropriate frequency channels and bandwidth to the mobile stations through the *wimax_mac* process model.

The *VS-Hypervisor* adequately apportions spectrum resources to individual virtual base-stations based on predefined spectrum allocation contracts (discussed in details in Chapter 4). Base-stations whose allocation depends on what they require per time have their allocations determined based on estimations through routine examination of subcarrier/symbol usage on each WiMAX frame transmitted/received by each virtual base-station. The functions and global variables that perform this estimations are declared in a newly defined header file and external c-code file known as the *wimax_vs_est (.h/ex.c)* which is accessible both by the *VS-Hypervisor* process model, *vs_hypervisor_proc* and the *wimax_bs_control* child process contained in the *wimax_mac* process model. A summary of these processes is summarized in Figure 3.10. Signalling communication between the base-station and the VS-Hypervisor is memory based which is permissible in OPNET as opposed to using data packets.

3.5 VS-Hypervisor Design

While Section 3.4 described the reference model for spectrum virtualization in OPNET, this section discusses in details how the VS-Hypervisor was designed to implement spectrum virtualization; in term of its node model, process model and Proto-C codes. It also explains the additional functions that was added to the VS-Hypervisor that enables it perform WiMAX network federation which is discussed later in Chapter 5.

3.5.1 VS-Hypervisor Node Model

The Figure 3.11 below shows the Node Model for the VS-Hypervisor after *double-clicking* on the VS-Hypervisor's node icon in the OPNET network modelling environment. It consists of a single node processor which performs the following functions:

- It invokes the OPNET WiMAX external Proto-C code files (*wimax_support.ex.c* and *wimax_phy_support.ex.c*) as well as the external C-code files for the VS-Hypervisor (*wimax_vs_estimator.ex.c*) via the VS-Hypervisor's process model (*vs_hypervisor_proc*) as depicted in Figure 3.12.
- It manages and invokes the VS-Hypervisor's process models both for network virtualization and federation as shown in Figure 3.13.
- It reconfigures the OPNET WiMAX base-station MAC layers through the VS-Hypervisor's process models to perform the process of virtualization, federation or both together.
- It manages the statistical data and graphs obtained during/after simulation as illustrated in Figure 3.14.

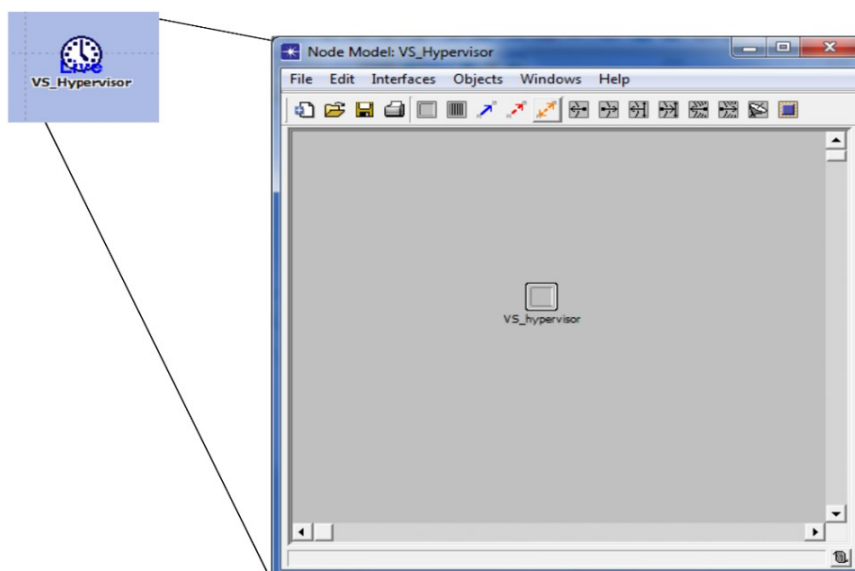


Figure 3.11 VS-Hypervisor Node Model.

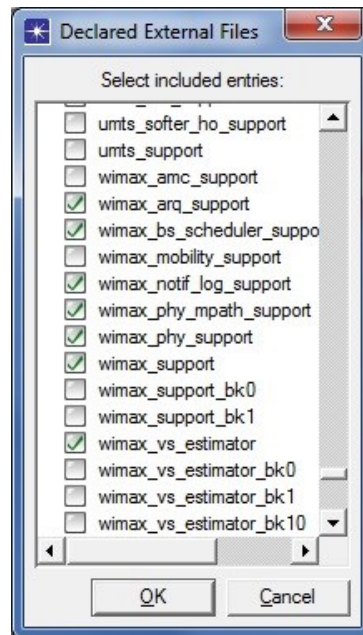


Figure 3.12 Invoked External C-code files by VS-Hypervisor Node Model.

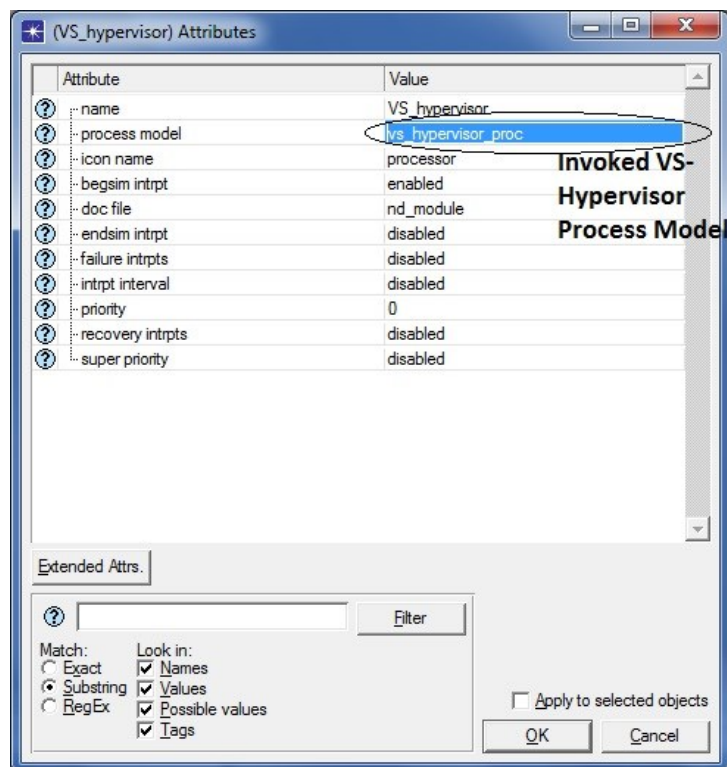


Figure 3.13 Invocation of the VS-Hypervisor Process Model by the Node Model.

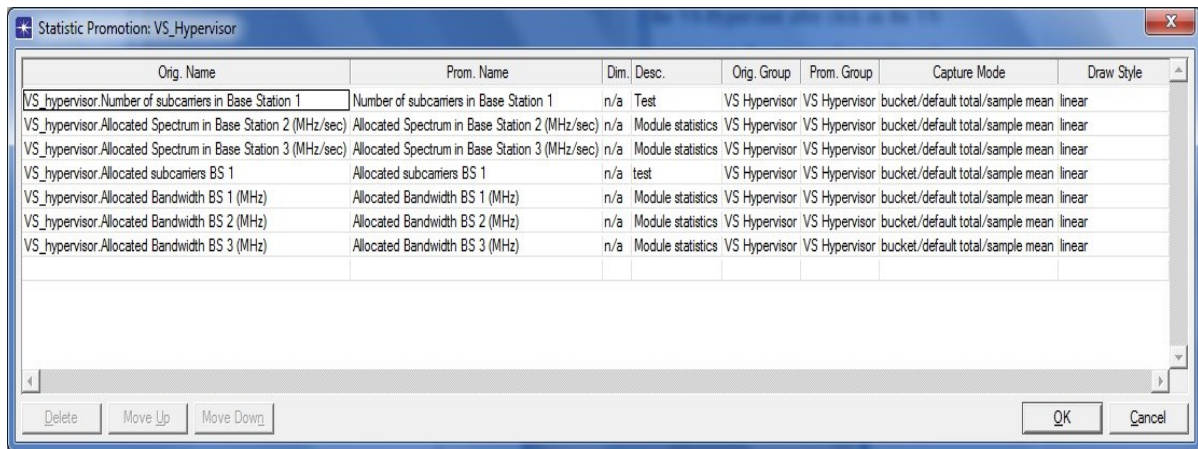


Figure 3.14 Statistics Configuration on the VS-Hypervisor.

The manner of statistics gathered by the VS-Hypervisor as shown in Figure 3.14 includes: the number of spectrum (FFT size) and bandwidth allocated per base-station.

3.5.2 VS-Hypervisor Process Model

This section describes the VS-Hypervisor's Process Models both for spectrum virtualization and network federation. This section also explains the interaction of all the component parts inside the VS-Hypervisor node that makes it function as a holistic system in the process of spectrum virtualization.

3.5.2.1 VS-Hypervisor Process Model for Spectrum Virtualization

The process model that implements WiMAX spectrum virtualization (*vs_hypervisor_proc*) is shown in Figure 3.15. The process model shows a state transition diagram with three (3) states. The function of each state is stated below:

- **State 1 (init1):** This state initializes the VS-Hypervisor to be in sync with the simulation time of the OPNET Modeler.
- **State 2 (init2):** This state initializes and synchronizes the VS-Hypervisor with the WiMAX frame transmission duration each time the base-station communicates with mobile station.

- **State 3 (Schdlr):** This is the state that puts the VS-Hypervisor in the spectrum slicing and scheduling mode i.e. the virtualization mode. It calls the *function* defined inside the process model that starts-up the virtualization process.

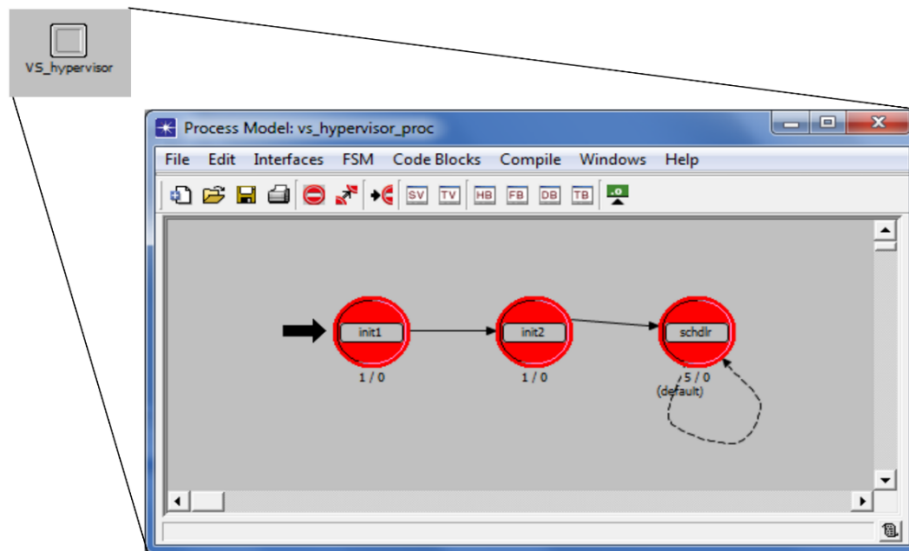


Figure 3.15 VS-Hypervisor Process Model for Spectrum Virtualization.

Within a process model in OPNET, an environment is made available to declare state variables (SV) that will be needed in the process model's operation. This environment is referred to as the SV block in OPNET. A snap-shot of the state variables used in the VS-Hypervisor is shown in Figure 3.16.

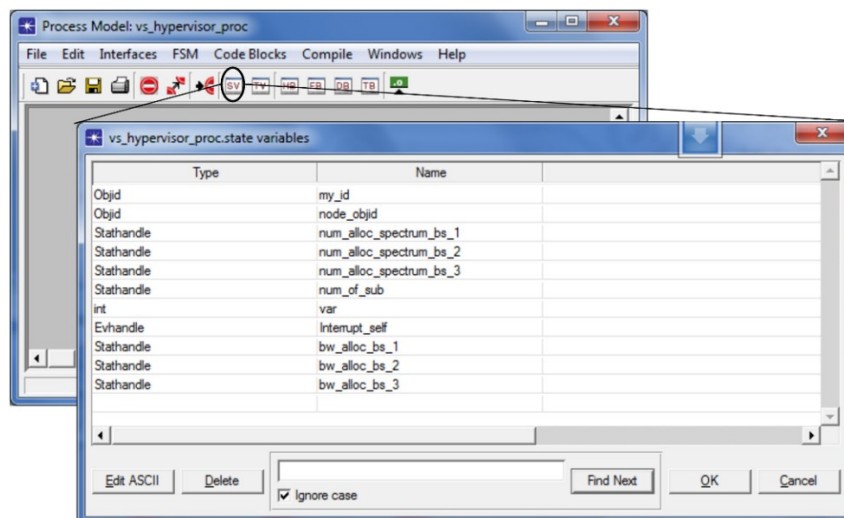


Figure 3.16 VS-Hypervisor State Variables declaration in the SV block.

The state variables declared in the VS-Hypervisor's process model are for identifying the node and process models of the VS-Hypervisor; for triggering the spectrum scheduling function in the *schdlr* state and for grabbing statistical values. For the VS-Hypervisor to be able to have access of the WiMAX MAC and PHY pre-defined variables and functions in OPNET, the header files (*wimax_support.h* and *wimax_phy_support.h*) that handles these functions and variables must be declared within the process model of the VS-Hypervisor node—in the header block (HB) environment as shown in Figure 3.17 alongside with other OPNET's operational header files.

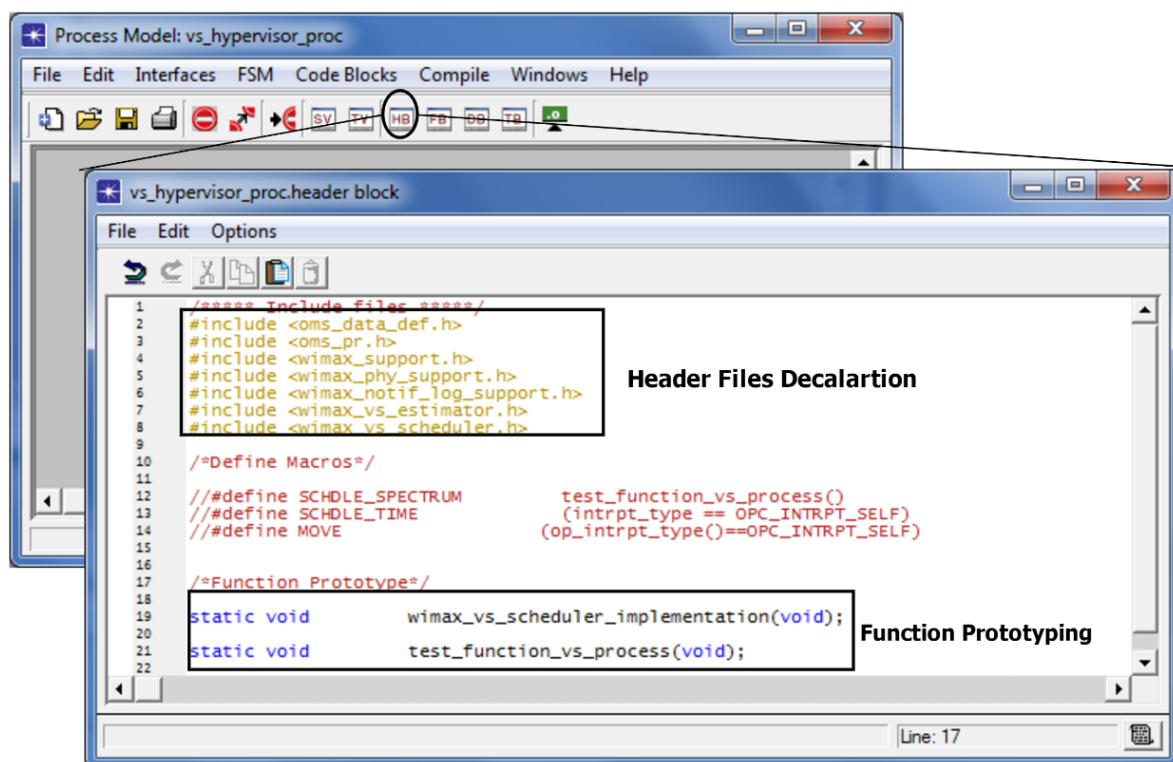


Figure 3.17 Header File Declaration and Function Prototyping in the Header Block (HB).

It is also within the header block of the VS-Hypervisor's process model that function prototyping is performed as shown in Figure 3.17. The definition of the prototyped functions are done inside the function block (FB) environment of the process model as shown in Figure 3.18. The functions declared in the VS-Hypervisor's function block (*wimax_vs_scheduler_implementation* and *test_function_vs_process*) interacts with global

variables and functions that are declared in the VS-Hypervisor's unique header file (*wimax_vs_estimator.h*) as well as with its corresponding external c-code file. A snap-shot of the VS-Hypervisor's header file and external c-code file is shown in Figure 3.19

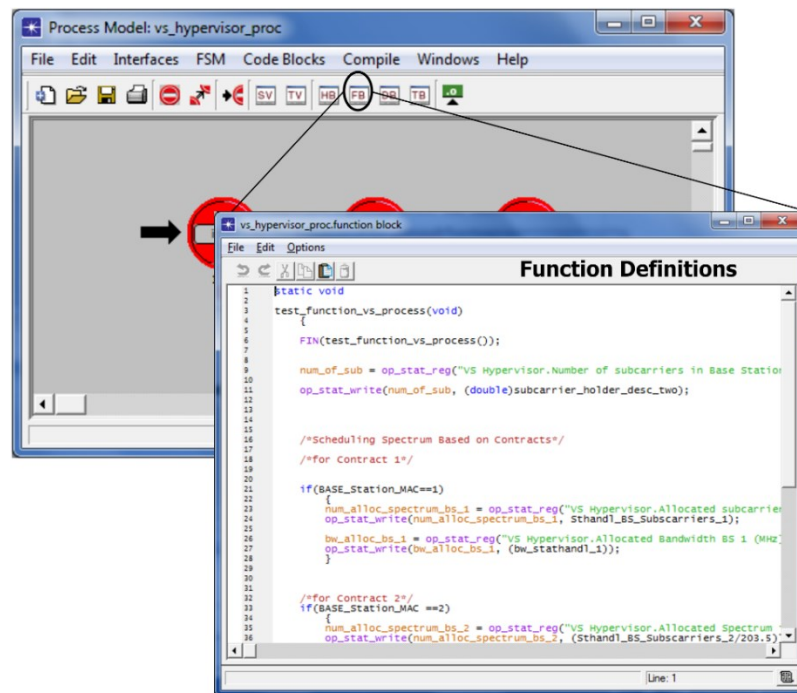


Figure 3.18 VS-Hypervisor Function Definitions in Function Block (FB).

The function/method defined in the external c-code file shown in Figure 3.19 performs the following activities:

- It performs ***FFT mapping*** and ***bandwidth (BW) mapping*** necessary for allocating spectrum to the virtual base-stations. The algorithms implemented by this function is outlined and explained in Section 4.4.2.3 of Chapter 4.
- It interacts with the MAC layer of each virtual base-station through the ***wimax_bs_control*** child-process model (explained earlier in Section 3.3.2.5) in order to be able to get the spectrum estimate as well as the service level agreement (SLA) contracts of the virtual base-stations (details in Chapter 4); which is necessary to determine their spectrum allocation. To effectively allocate spectrum to the virtual

base-stations, the VS-Hypervisor needs to have full access to spectrum resources of the physical base-station.

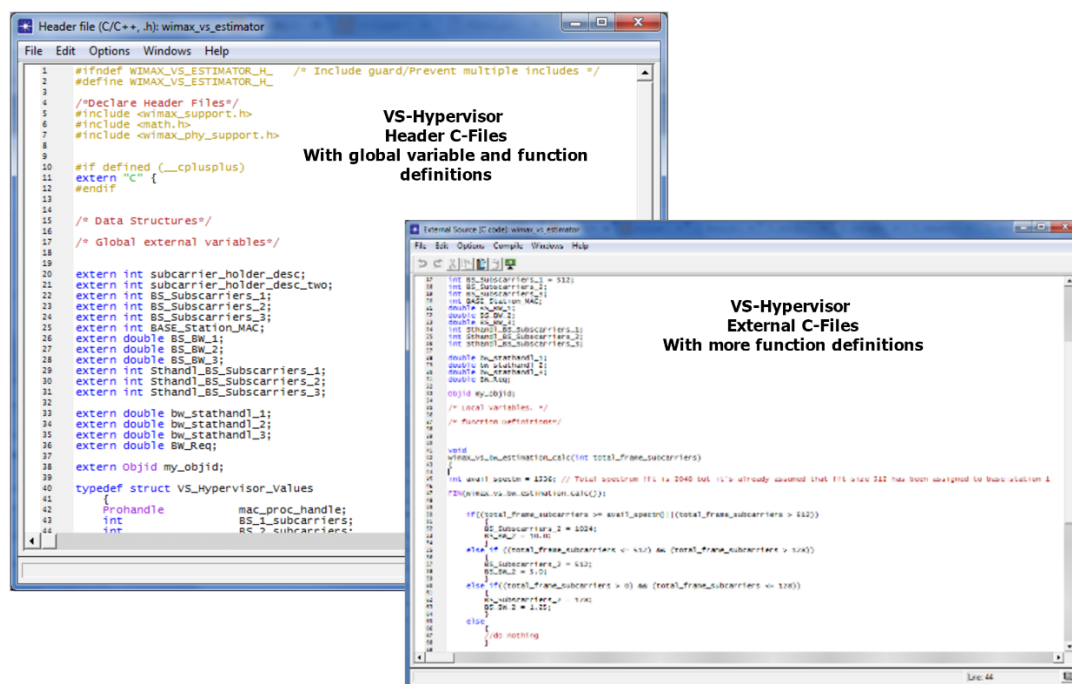


Figure 3.19 VS-Hypervisor Header File and External C-Code Files.

3.5.2.2 VS-Hypervisor Spectrum Access

To have access to the entire spectrum (OFDMA subcarriers) of the physical base-station, the VS-Hypervisor's process model (*vs_hypervisor_proc*) needs to do the following:

- Invoking a function using OPNET specific Application Program Interface (API) functions in order to have access to the OPNET global repository (See **Appendix A**), where WiMAX PHY parameters are stored.
- Interconnect with the WiMAX OPNET PHY external c-code support files (*wimax_support.ex.c* and *wimax_phy_support.ex.c*) using global variables and memory locations as well as define hooking functions (i.e. functions defined to reconfigure the PHY arrangement for each virtual base-station) inside *wimax_bs_control* process model of every virtual base-station.

To provide clarity on how the VS-Hypervisor's process model interacts with its header files, its external c-code files, the *wimax_bs_control* process model per virtual base-station and the

OPNET global repository. A sequence diagram showing the flow of signalling events is illustrated in Figure 3.20.

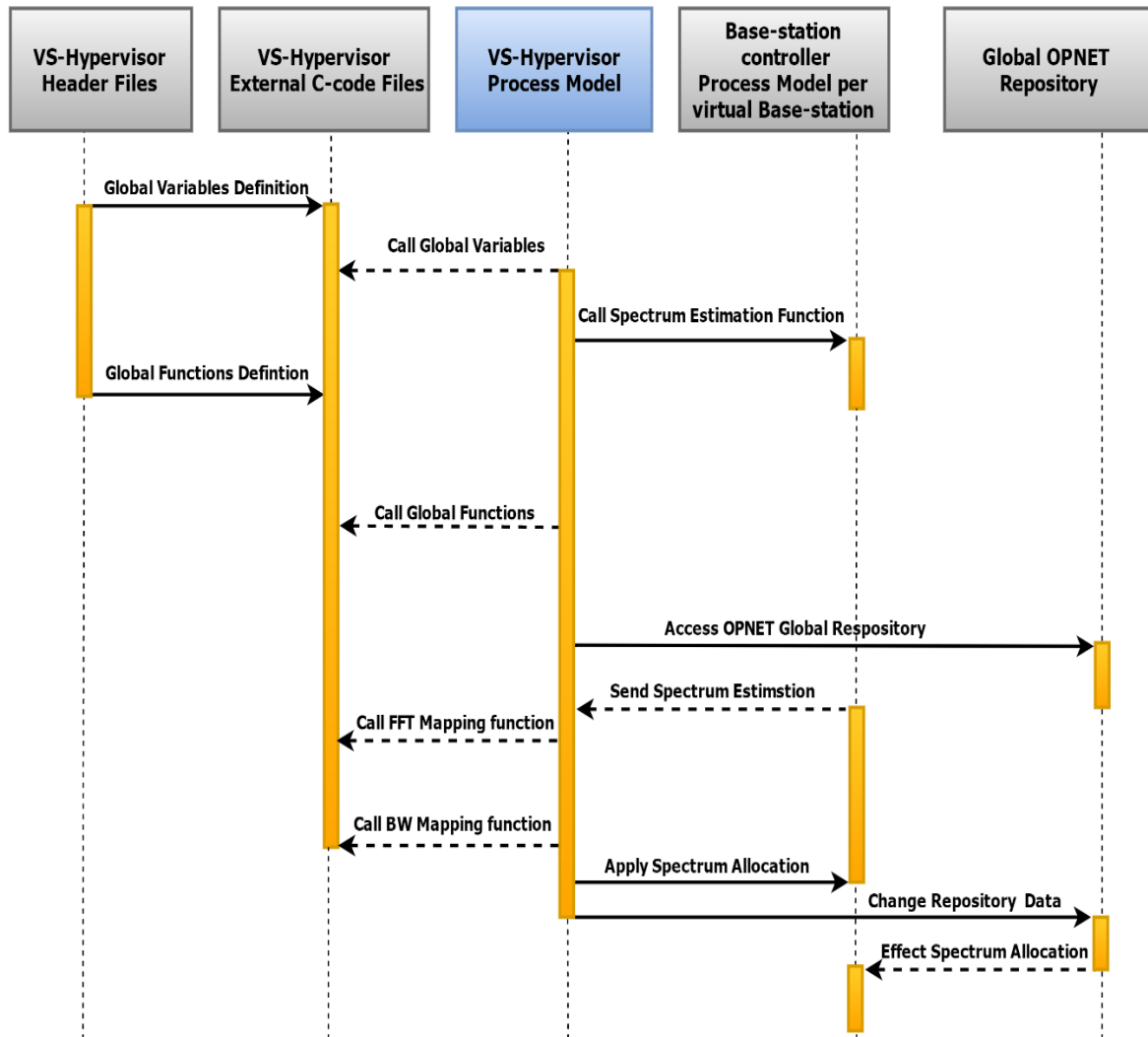


Figure 3.20 VS-Hypervisor Sequence Diagram.

It can be seen from the sequence diagram in Figure 3.20 that there are five objects—VS-Hypervisor Header Files, VS-Hypervisor External C-code files, VS-Hypervisor Process Model, the Base-station controller process model (*wimax_bs_control*) per virtual base-station and OPNET Global Repository. The sequence of events is as follows:

-
- The VS-Hypervisor's Header files send declared variables and prototyped functions for `Global Variables Definition` and `Global Functions Definition` for handling by the VS-Hypervisor External C-code files.
 - The VS-Hypervisor's Process Model then sends the message `Call Global Variables` to the VS-Hypervisor's External C-code files for initialization; at the same period it sends a message `Call Spectrum Estimation Function` to the Base-station controller's process model.
 - Following the last sequence, the VS-Hypervisor's Process Model also sends `Call Global Function` message in order to get the spectrum estimation (number of OFDMA subcarriers) of each virtual base-station (more of this is discussed in Chapter 4) and during the same period a message `Access OPNET Global Repository` is sent to the OPNET global repository object using OPNET specific API functions to have access to the WiMAX PHY parameters.
 - After the above step, the virtual base-stations send their spectrum estimations using the `Send Spectrum Estimation` message to the VS-Hypervisor's Process Model for spectrum allocation. Thereafter the `Call FFT Mapping Function` and `Call BW Mapping Function` messages are sent and retrieved from the VS-Hypervisor's External C-code files.
 - Having received the spectrum estimation for the virtual base-stations, the VS-Hypervisor's process model provides spectrum allocation by sending the message `Apply Spectrum Allocation` to the virtual base-stations and at the same time, it makes WiMAX PHY parameter changes to the OPNET global repository by using the signal `Change Repository Data`.
 - Finally, the OPNET global repository sends a message `Effect Spectrum Allocation` to the virtual base-stations to finalize the changes to their WiMAX PHY parameters.

3.5.2.3 VS-Hypervisor Process Model for Federation

To implement WiMAX network federation, an additional state called *federate* is added to the initial VS-Hypervisor process model and the new process model is renamed *vs_hypervisor_proc_fed* as shown in Figure 3.21. The *federate* state serves the purpose of negotiating for spectrum allocation between multiple physical base-stations in a cooperative manner. The *federate* state makes the VS-Hypervisor to operate like a control plane module (more details are discussed in Chapter 5). The sequence diagram showing the exchange of messages between the VS-Hypervisors for federation between two physical base-stations is depicted in Figure 3.22.

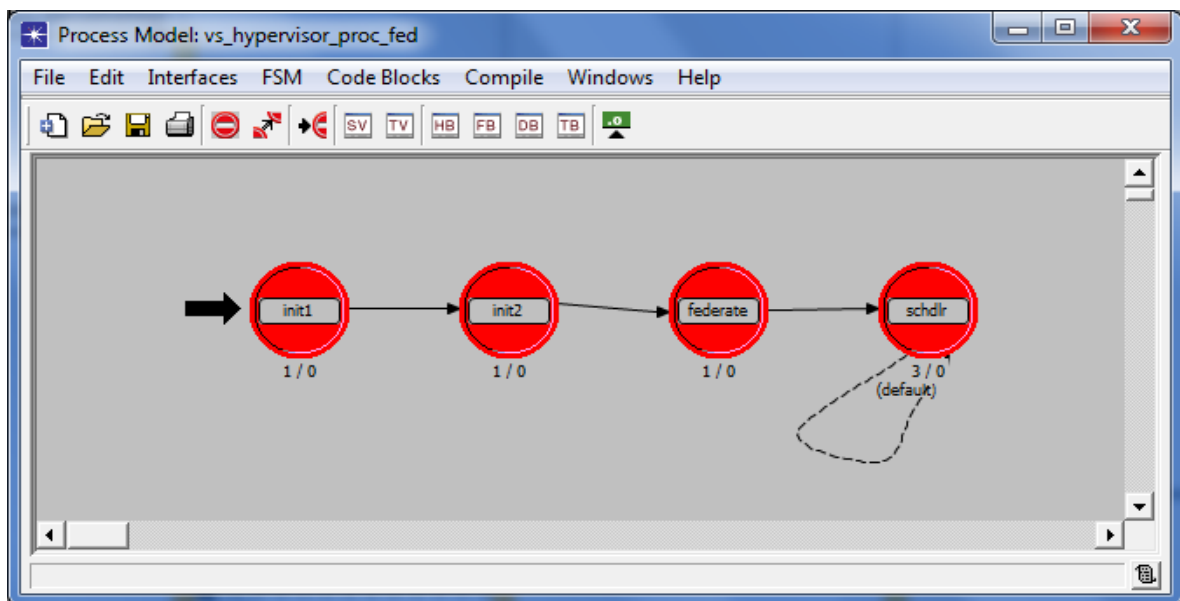


Figure 3.21 WiMAX Federation Process Model.

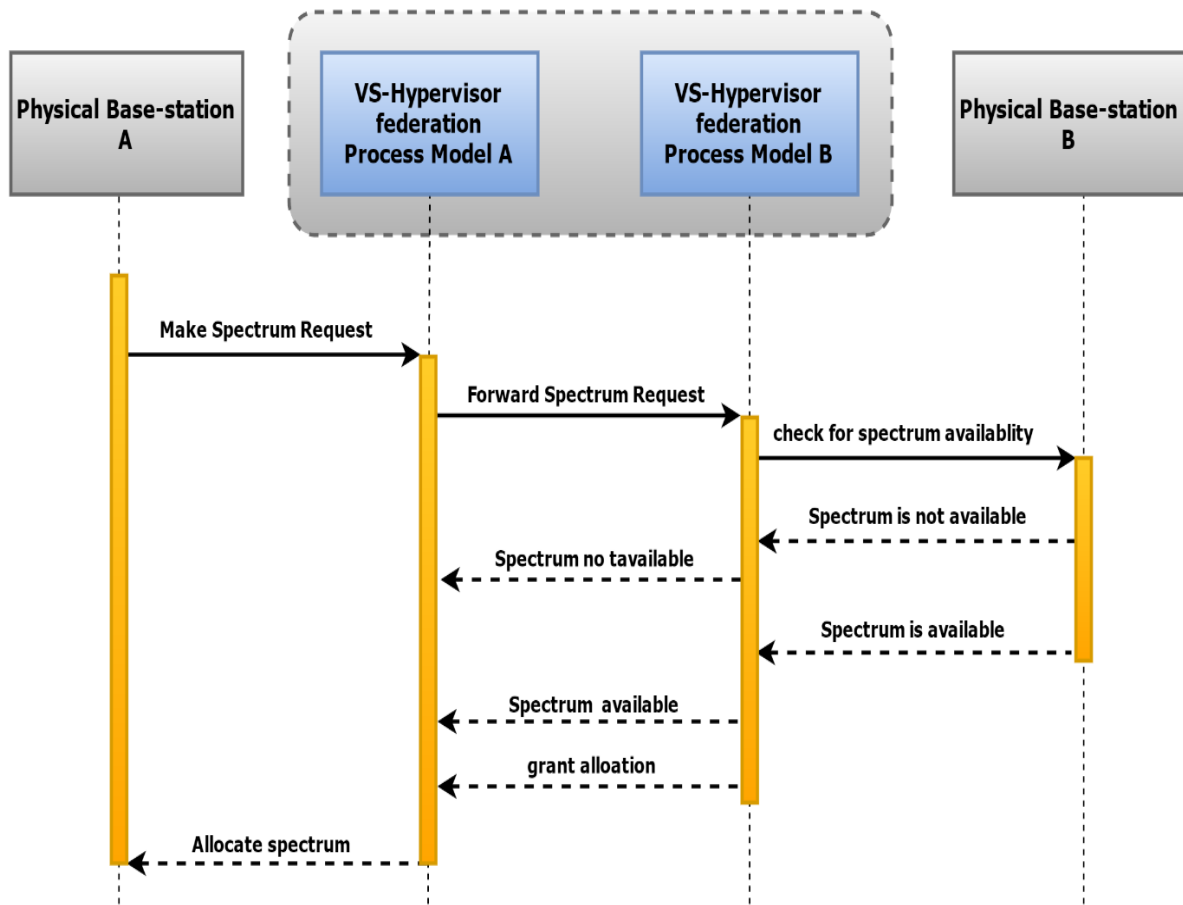


Figure 3.22 Sequence Diagram of VS-Hypervisor Federation.

The sequence of events that makes up the federation process for spectrum negotiation and allocation shown can be explained further as follows:

- A physical base-station (A) sends a spectrum request message `Make Spectrum Request` through its VS-Hypervisor (A). Its VS-Hypervisor then forwards the request using a message `Forward Spectrum Request` to the VS-Hypervisor of the physical base-station (B).
- The VS-Hypervisor of Base-station (B) checks if there is spectrum available by sending the message/signal `Check for Spectrum Availability` to Base-station (B). Base-station (B) acknowledges this message via its VS-Hypervisor by either sending

the messages `Spectrum is not available`, if `spectrum is not available`, or `Spectrum is available if there is spectrum`.

- If `spectrum is not available`, the VS-Hypervisor of Base-station (B) replies the VS-Hypervisor of Base-station (A) with the message `Spectrum not available` and if it the case is contrary, the message `Spectrum is available` is sent. If `spectrum is available`, it grants the spectrum allocation to Base-station (A) VS-Hypervisor using the message `grant allocation`.
- Finally, the VS-Hypervisor of base-station (A) that configures its base-station with the new spectrum allocation; expressed in the message `Allocate spectrum`.

3.6 Software Testbed Qualitative Description

The description of the software testbed developed in the research in terms of the qualitative description of the code, testing and deployment is covered in this section and they are addressed as follows:

- **Implementation:** As earlier stated, the proto-c programming language is used in designing the software testbed used in the research. The proto-c codes basically implements the VS-Hypervisor's sequence models both for spectrum virtualization and network federation. The proto-c programming code is used in building header files where user specific global variables and functions are declared in relation to the testbed design. The proto-c programming language is also used in defining the declared functions that carry-out the operations of spectrum virtualization and network federation. The interworking of these functions within the OPNET Modeler platform is already described in Figure 3.10.
- **Integration and Testing:** The software tested is fully integrated in the OPNET 14.5 Modeler and a bug-free and error-free working prototype has be submitted to the relevant authority representing the University of Cape Town (The Supervisor of this research).
- **Acceptance, Installation and Deployment:** The testbed is fundamentally a simulation tool and can only function with the OPNET Modeler platform. It cannot be installed

and deployed independently. Its design is not for real-life application and therefore a real-life functionality acceptance cannot be assessed. To deploy the testbed will involve setting-up a WiMAX network project in OPNET Modeler and utilizing the VS-Hypervisor entity which is node entity in the OPNET Modeler WiMAX Spectrum Virtualization tool pallet.

3.7 Summary

This Chapter explained and discussed in detail the features of OPNET Modeler as a research modelling tool for the design and simulation of communication networks. The OPNET Modeler environment consists of four hierarchical editors comprising of the Project editor, Node editor, Process editor and the open model source-code. The OPNET modeller 14.5 which was used for this research contains a WiMAX network module/toolbox for modelling WiMAX networks and it allows for the addition of new features to the existing design. The WiMAX module located in OPNET Modeler is designed based on the IEEE.802.16e standard. At the heart of every node object in OPNET Modeler is the node model and the process model which comprises of state transition diagrams which are programmed with the Proto-C programming language; which is an offshoot of the C/C++ programming languages. Also discussed was how spectrum virtualization was implemented in OPNET Modeler with the design of a new network object (VS-Hypervisor) consisting of its own node and process model having the ability to connect to the base-station's MAC process model in order to implement the idea of spectrum virtualization through the re-scheduling and re-allocation of spectrum resources.

Chapter 4 WiMAX Spectrum Virtualization

Implementation

In Chapter 1, a brief rundown was made on the idea of spectrum virtualization as well as wireless virtualization. However in this Chapter, the basic idea of *virtualization* is discussed—describing its evolution and all the facets that it covers. Also, this Chapter discusses how spectrum virtualization was achieved for WiMAX, using a novel model with results validating its efficacy through simulations done using the OPNET Modeler. A performance analysis based on selected metrics is carried out principally to determine how spectrum virtualization of a WiMAX network compares with a non-virtualized WiMAX network.

4.1 Explaining the Concept of Virtualization

Virtualization can basically be defined as the abstraction of physical resources for the purpose of sharing them among different parties. The concept of *virtualization* and its origin is mostly accepted to have started in the 1960s and early 1970s by the International Business Machine (IBM) when they invested a lot of time and resources in developing full-bodied time-sharing solutions [53], [54]. Time-sharing can be described as the sharing of computer resources among a large group of users with the aim of increasing the efficiency of both the users and the computer resources that is being shared. It heralded a breakthrough in computer technology.

The first mainstream implementation of virtualization on a computer (IBM Mainframe) was done by Gerald J. Popek and Robert P. Goldberg; where they developed a coded framework to support virtualization on a computer. In a publication by Popek and Goldberg [55], they came up with the idea of Virtual Machines (VM) and Virtual Machine Monitor (VMM) generally known today as a *hypervisor*. By their definition, a VM is capable of virtualizing the hardware

resources of a computer most especially processors, storage, memory and network connectivity. The VMM or hypervisor is the software that creates the enabling environment for the VM to function [56]. The Figure 4.1 shows an example of a VMM/Hypervisor for a computer. The virtual machines are referred to as *guests* having their own separate operating systems (OS).

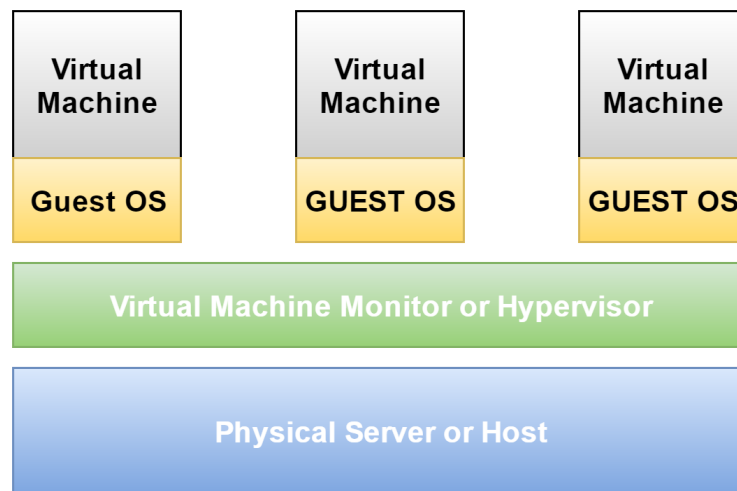


Figure 4.1 A Basic Virtual Machine Monitor.

According to [55], for a VMM or a hypervisor to fully satisfy its definition, it needs to demonstrate these three properties listed below:

- **Fidelity:** It must create an environment for the VM which is identical to the original hardware machine.
- **Isolation:** The VMM or Hypervisor must have full control of the system resources.
- **Performance:** There should be no difference in the performance of the VM when compared the physical equivalent [56].

Generally, hypervisors are usually classified into two categories based on where they are situated in the host's hardware. The two categories of hypervisor are: Bare-Metal/Native Hypervisor and Hosted Hypervisor. Details of their characteristics are shown in Table 4.1.

Table 4.1 Types of Hypervisors.

Hypervisor Type	Characteristics
Type 1: Bare Metal/ Native	Bare Metal hypervisors are software systems that control the hardware of a host by running directly on them. As a result, the guest OS or virtual machine run on a separate level above the hypervisor. E.g.: Oracle VM, Xen, Microsoft Hyper-V and VMWare ESX.
Type 2: Hosted	The hosted hypervisors are software systems fashioned to operate within a conventional operating system i.e. that add an additional layer of top of the host's OS, thereby making the guest OS to become a third software level above the hardware. E.g.: VMware VirtualBox, QEMU and Parallels.

4.2 Virtualization Techniques

It is clear from Section 4.1, that the idea of virtualization started from the computer system domain. During its developmental stages, several techniques were applied in its implementation and these techniques have formed the foundation upon which other areas of virtualization have been applied. This section discusses the various techniques of virtualization applied in computer systems especially as it relates to this research work.

4.2.1 Guest Operating System Virtualization

The guest operating system virtualization is also referred to as an application based virtualization. This is essentially the easiest concept of virtualization to grasp. It involves a host computer system running a standard OS such as Windows, Linux or Mac OS X. Installed on this OS is a virtualization application (e.g. VMware Server) which executes like any other computer application e.g. MS Word. It is inside this virtualization application that one or more virtual machines are created. The created virtual machines run their individual or separate guest OS all within the host computer. The application bears the responsibility of controlling each

virtual machine and their access to the computer's physical hardware resources [57], [58]. The Figure 4.2 provides an illustration of a guest OS virtualization.

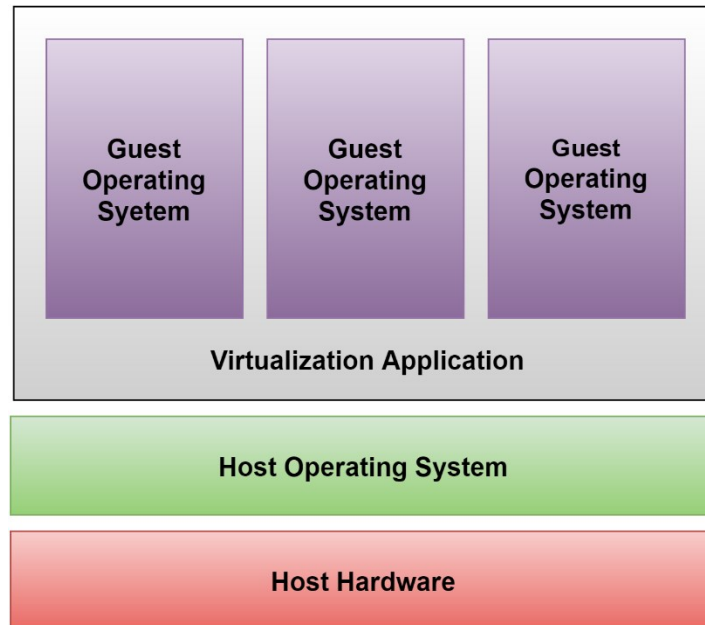


Figure 4.2 Guest OS Based Virtualization.

4.2.2 Hypervisor Virtualization

In the hypervisor virtualization, the hypervisor or VMM runs directly on the host system's hardware. The responsibility of the hypervisor is to handle resource and memory allocation for the virtual machines as well as providing an interface for higher level administration and monitoring. A typical representation of hypervisor virtualization is similar to the diagram shown earlier in Figure 4.1.

4.2.3 Full Virtualization

In this approach, a complete replica of the real hardware is virtualized to allow the guest operating system to function without any amendments as illustrated in Figure 4.3. It also has a hypervisor layer that provides the platform for the virtual machines to run on top of the physical hardware [59].

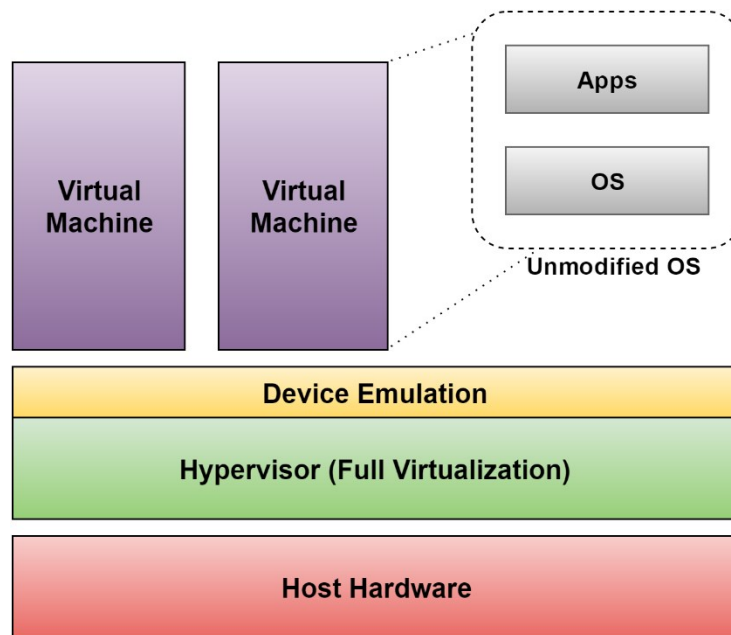


Figure 4.3 Full Virtualization.

4.2.4 Para-virtualization

In contrast to full virtualization, para-virtualization (PV) does not mirror the hardware environment in the hypervisor, rather it organises the hardware resources to make it easily accessible to the virtual machines. The hypervisor in this case acts as a host on which the guest operating systems are loaded. Guest operating systems will make the required system calls to the hypervisor for the utilization of the hardware resource [60], [61], [62]. The para-virtualized version of hardware virtualization delivers better performance benefits when a VM's operating system runs in a virtualized environment where the modifications done to the VM is being virtualized [59]. Examples of para-virtualization softwares are Xen-PV, ESXserver, KVM-PV etc. A depiction of para-virtualization is shown in Figure 4.4.

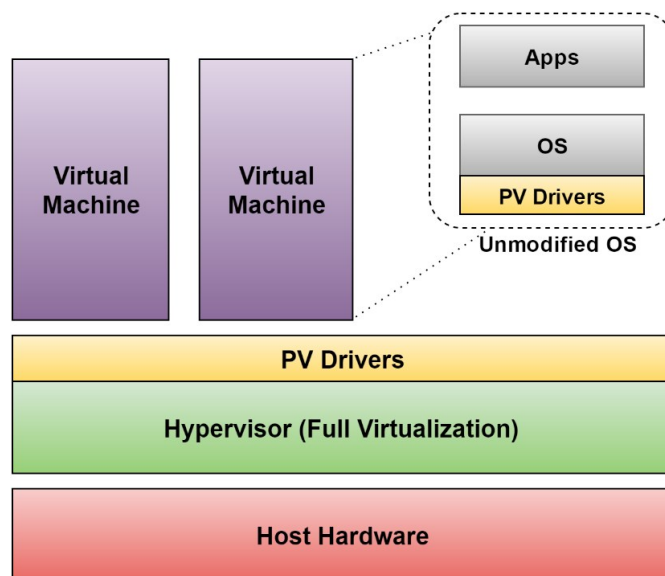


Figure 4.4 Para-Virtualization.

4.3 Network Virtualization

Network virtualization typifies the steady evolution from host or computer virtualization previously discussed. The terminology *network virtualization* is a wide-ranging term that refers to diverse concepts in relation to different contexts [3], [63], [64]. According to [65], Network virtualization can be described as the decoupling of the functionalities in a network environment by separating the roles of conventional internet service providers (ISP) into two, namely: Infrastructure providers (InPs) and service provider (SP). The InPs have the responsibility of managing the physical infrastructure and the SPs assist in creating virtual networks by combining resources from multiple InPs and providing end-to-end network services. In more specific terms, network virtualization can be better described as a network environment that enables multiple SP to dynamically create multiple heterogeneous virtual networks to function together in isolation. With such an arrangement, service providers can set-up and manage customized services for end-users to share and utilize. This technology is often denoted as software defined networking (SDN) [66], [67]. The Figure 4.5 illustrates a basic model for network virtualization; showing a network substrate which is a physical network node with the capability for supporting virtual nodes [68]. Some of the recent global projects in network virtualization include: UCLP [69], VIOLIN [70] and VNET [71] where the

focus was on layers of virtualization; FEDRICA [72] focusing on architectural domain and management; and 4WARD [73], VINI [74], PlanetLab [75] and CABO [76] focused their attention on the granularity of virtualization [77]. Table 4.2 shows the strength and limitations of these network virtualization projects.

Table 4.2 Strength and Limitation of Network Virtualization Projects.

Network Virtualization Project	Strength	Limitation
UCLP	Dynamic provisioning and reconfiguration of light-paths.	It is a physical layer based virtualization platform. Its level of virtualization is based on communication links. It is not an IP based technology.
VIOLIN	Deploying an on-demand value added services on IP overlays.	Its layer of virtualization is limited to the application layer. It supports only node based virtualization.
VNET	Isolates traffic between slices. Supports a unique interface for accessing proxied IP addresses.	It is a PlanetLab network access technology.
FEDRICA	Creating a virtual circuit between two virtual systems with a specified assured capacity.	It is a node and link layered virtualization platform.
4WARD	Virtualization of diverse network resource types in a common framework.	Lack of standardization
VINI	Evaluated protocols and services in a realistic environment.	Its level virtualization is based on communication links. It is not an IP technology.
PlanetLab	Deploying and managing overlay-based testbeds.	Its layer of virtualization is limited to the application and physical layer.
CABO	Deploying a value-added end-to-end services on shared infrastructure. Full virtualization is its level of virtualization.	It is not an IP technology.

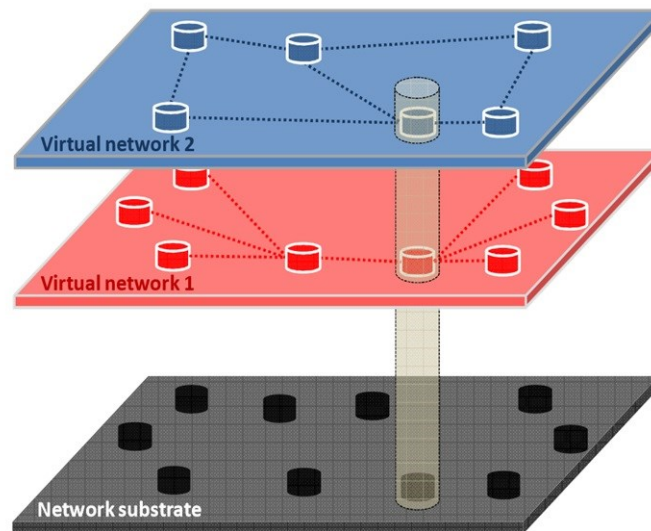


Figure 4.5 Basic Network Virtualization Model [68].

Amongst all the network virtualization projects listed in Table 4.2, the 4WARD project embodies some of the key features of this research, most especially their proposed business model for network virtualization. This is further discussed in Section 4.3.1.

4.3.1 4WARD Project

The 4WARD project is European project established in the year 2008 to investigate two technical areas:

- A comprehensive framework for the provision and the deployment of large-scale, end-to-end virtual networks (VNet).
- Efficient virtualization of network resources [78].

In addition to the network virtualization provider roles of the InP and SP, the 4WARD project proposed a more fine-grained business model comprising of three provider roles. This was based on the recognised fact that network virtualization possesses the potential to facilitate a variety of new scenarios and business opportunities. The provider may choose to occupy different parts of the value-chain and develop their own business strategies. The network virtualization provider roles suggested by 4WARD besides the InP are:

- **Virtual Network Provider (VNP):** Creates virtual networks by using virtual resources and the fractional topologies administered by the InP or other VNPs [78].
- **Virtual Network Operator (VNO):** Operates, manages and controls virtual network for the purpose of providing services [78].

The Figure 4.6 below shows the 4WARD three basic provider roles.

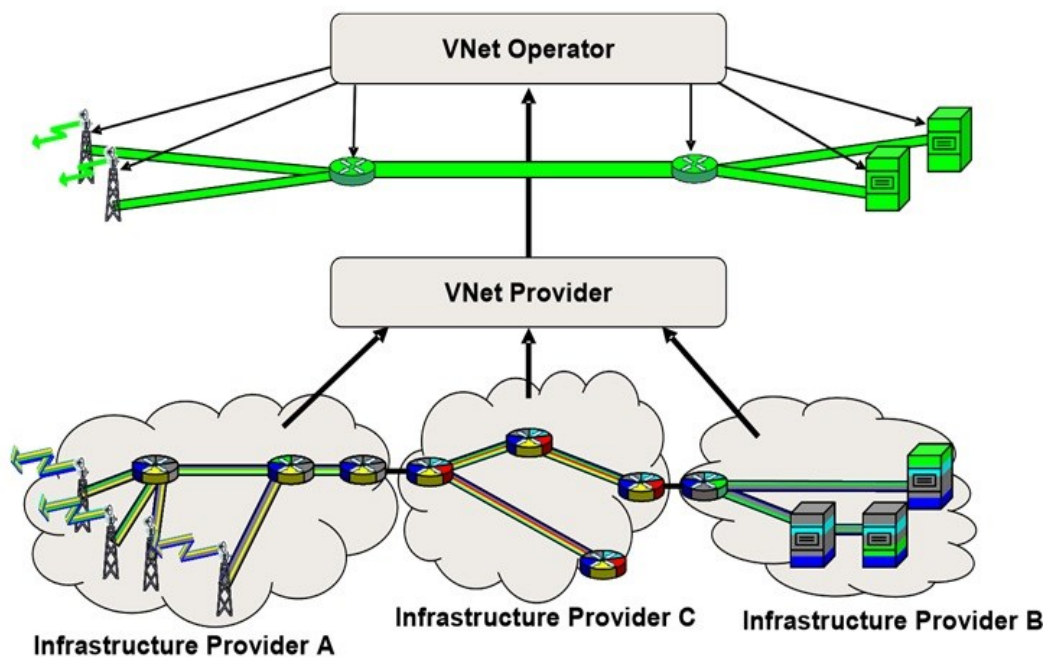


Figure 4.6 4WARD Provider Roles [78].

4.4 Wireless Virtualization

This section underscores the focus of this research which is the virtualization of the wireless medium or spectrum. In today's world, considerable amount of momentum has been gained by wireless technologies and this is due to the astronomical growth in mobile computing.

As a result of this, there has been an increase in the amendments of existing wireless standards and the introduction of newer standards resulting in a chaotic competitive environment in the mobile communication space. With the existence of such heterogeneous environment, there is a need to proffer solutions that will enable the interoperability and the harmonization of their

resources. The abstraction of the wireless spectrum provided through virtualization is a possible solution to this problem. In wireless virtualization, a resource can be regarded as wireless equipment such as an entire base-station and it could also be referred to as PHY resources such as time-frequency slots as well as the entire wireless spectrum. These resources can either be shared or *partitioned* [3], [78].

4.4.1 Perspectives of Wireless Virtualization

Wireless virtualization encompasses different perspectives in terms of specific applications and design goals. This section looks at the three core different viewpoints based on the kind of resources that is being virtualized as well as the debt of the resource partitioning/slicing.

4.4.1.1 *Flow-based and Data Wireless Virtualization*

A stream of data that is shared while having a common labelled identity can be described as a flow. Flow-based virtualization is motivated by SDN technologies such as OpenFlow [79], [80]. It aims at providing isolation, scheduling, service-differentiation and management operations both in the uplink and downlink traffic flow direction for all the individual slices. Flow-based virtualization can be integrated into the internal MAC scheduler of a wireless technology in order to use resource sharing algorithms to reinforce QoS requirements or contracts for each slice.

The vBTS architecture and the NVS architecture for WiMAX virtualization mentioned in Sections 1.2.1 and 1.2.2 are typical examples of a flow-based virtualization. Another example of flow-based virtualization is the virtualized eNodeB for LTE mentioned in Section 1.2.3 whereby a modified MAC scheduler was used to isolate the resource scheduling for each slice. In flow-based virtualization, every slice shares the same protocol stack [3].

4.4.1.2 Protocol-Based Wireless Virtualization

In contrast to flow-based virtualization, protocol-based virtualization provides a distinctive viewpoint to wireless virtualization. It involves the isolation, customization and the management of many protocol instances in a single radio hardware. The kind of resource being sliced depends on the wireless protocol that is being handled by the hardware platform. If it is on the MAC layer, it could be protocol decomposition or scheduler virtualization. On the PHY layer, it could be the allocation of hardware Digital Signal Processing (DSP) resources. An example of a protocol-based virtualization is the Power Saving Mode (PSM) and Point Coordination Function (PCF) based virtualization for wireless network interface cards (NIC) [81] where some enhancements was done on the MAC layer.

4.4.1.3 RF Frontend and Spectrum-based Wireless Virtualization

At the current stage of wireless virtualization, RF frontend and spectrum-based virtualization constitutes the deepest form of slicing. It is comprised of the abstraction and the dynamic allocation of the frequency spectrum to each virtual node or transceiver through spectrum restructuring and radio slicing techniques. It permits a particular protocol stack to have random access to non-contiguous frequency bands and it decouples the RF frontend from the protocols enabling a single frontend antenna to be used by multiple virtual wireless nodes. The SVL virtualization approach performed in the digital domain and discussed earlier in Section 1.2.4 virtualizes the wireless spectrum by using intermediary signal processing techniques to perform spectrum re-shaping and re-mapping.

In Section 1.2.5, the discussed Picasso approach to wireless spectrum virtualization which functions in the analogue domain, makes modifications in the RF frontend which allows full-duplex transmission of signals on a single antenna ensuring spectrum isolation between slices [3].

4.4.2 WiMAX Spectrum Virtualization

Present-day research trends practically in the area relating to the future of mobile communication, points in the direction of resource sharing between heterogeneous networks.

To realize the objectives of this new paradigm, network resource virtualization mostly in the wireless domain, is gaining recognition as one of the key technological solutions.

Wireless network resource sharing is born out of the need to increase the availability and extend the accessibility of scarce resources (e.g. RF Spectrum) and it also ensures that these resources are efficiently utilized. Spectrum-based wireless virtualization can be implemented on cellular broadband technologies. This thesis demonstrates and validates its implementation using the WiMAX framework. WiMAX is still a leading mobile communication technology and the virtualization of its spectrum will further make it competitive in the mobile communication business environment.

To virtualize the WiMAX spectrum certain assumptions have been made in this research:

- The WiMAX base-station infrastructure is already virtualized. Currently Alcatel-Lucent is planning on introducing a virtualized radio access network (RAN) due for trials in 2016 [82].
- The RF frontend of the WiMAX base-station supports full-duplex communication based on the Picasso model previously discussed.

4.4.2.1 Spectrum Virtualization Architecture

The WiMAX spectrum virtualization architecture proposed in this research is based on the spectrum-based wireless virtualization perspective described in section 4.4.1.3; having some similarities with the Picasso model [21] as shown in Figure 4.7. The architecture is also structured in a similar manner to the LTE spectrum virtualization platform [1] discussed in Chapter 1, section 1.2.3 . It utilizes a hypervisor layer similar to the hypervisor virtualization technique earlier explained in Section 4.2.2; where the hypervisor has been renamed as the VS-Hypervisor (Virtual Spectrum Hypervisor). In the proposed architecture, it shows that the WiMAX base-station has been virtualized into multiple virtual base-stations; in this instance they are three: VB₁, VB₂ and VB₃ with an assumption that they are all being used by different virtual network operators (VNOs).

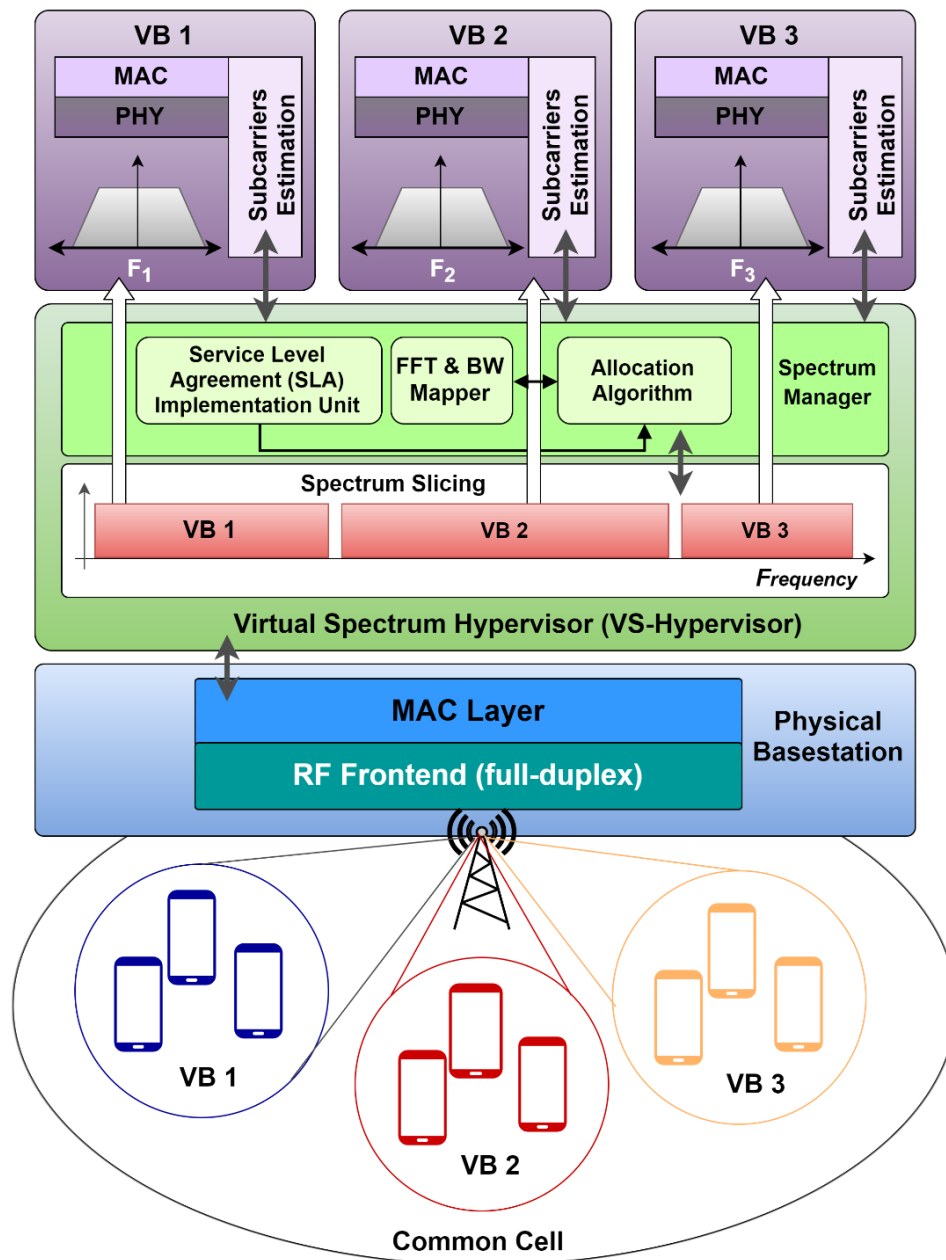


Figure 4.7 WiMAX Spectrum Virtualization Architecture.

Within each VB is a subcarrier estimation module (explained in Section 4.4.2.2) designed for calculating the amount of OFDMA subcarriers needed by each VB. This will determine the spectrum slice or partition to be allocated to them by the VS-Hypervisor. The VS-Hypervisor layer contains a spectrum manager for performing spectrum management functionalities using sub-units such as the service level agreement (SLA) unit, the FFT mapper and the allocation

algorithm. These sub-units are explained in details in Section 4.4.2.3. Based on the activities performed by the spectrum manager, the VS-Hypervisor partitions/slices the spectrum resource available to the physical base-station before allocating the partitioned spectrum blocks to the individual WiMAX VBs. Since this architecture assumes a full-duplex RF frontend, the VBs share the antenna of the physical base-station and transmit their signals simultaneously and independently on separate protocol stacks without any interference.

4.4.2.2 Subcarriers Estimation

The virtual base-station subcarriers estimation module performs its operation using an inductive scanning algorithm [83]. The scan is performed at every WiMAX frame interval of 5.0 ms to determine the total of number subcarriers allocated by a virtual base-station to its subscribers at its initial stage of connection. It performs this process by checking the downlink sub-frame for the number of subcarriers allocated which will determine the amount of spectrum and bandwidth to be allocated to the base-station for the next transmission. The VS-Hypervisor using this algorithm scans a sequence of subcarriers in a frame X_1, \dots, X_n where n is a collection of block-subsamples of the sequence of subcarriers and having the following properties:

- For every collection of block-subsamples, there is a single block of size $k = 1, \dots, n$.
- The n blocks are nested, i.e. the block of size k_1 can be found within the block of size k_2 when $k_1 \leq k_2$.

The total number of subcarriers inside the scan which is represented by the value ES_{total} will be the summation of the sizes of scanned blocks. And this can be expressed as:

$$ES_{total} = \sum_{i=1}^n k_i \quad (4.1)$$

After the estimation process, the estimated value is sent to the spectrum manager within the VS-Hypervisor for appropriate mapping and allocation. Figure 4.8 shows in the code of the function (*wimax_bs_control_scan_frame_process*) that implements the sub-carrier estimation algorithm in OPNET.

```

static void
wimax_bs_control_scan_frame_process (WimaxT_Ms_Scan_Mode_State* ms_scan_state_ptr)
{
    /** The function starts scan mode with the          */
    /* MS.                                             */
    FIN (wimax_bs_control_scan_frame_process ());

    /* Start the scanning mode on the corresponding MS node */
    /* by sending an unsolicited MOB_SCN-RSP.             */
    wimax_mob_scan_response_start (data_plane_config_ptr, ms_scan_state_ptr, phy_profile_ptr);

    FOUT;
}

```

Figure 4.8 Frame Scanning Function Code.

4.4.2.3 VS-Hypervisor Spectrum Management

As stated earlier in Section 4.4.2.1, the VS-Hypervisor performs the responsibility of spectrum management on the physical base-station by allocating spectrum to the virtual base-stations based on service level agreement (SLA) contracts through the application of an allocation algorithm. The SLA contracts are structured into three categories:

- **Fixed Allocation (FA):** In this allocation, the virtual network operator/virtual base-station is given a fixed amount of spectrum (FFT OFDM subcarriers) along with its corresponding bandwidth. The allocation will not be revoked even if it is unused. This allocation takes first priority in the SLA contract hierarchy.
- **Dynamic Allocation (DA):** Spectrum allocation and the corresponding bandwidth is provided to the virtual network operator/virtual base-station based on its estimated need (ES_{total}) per frame duration. The allocation is bounded by the available spectrum after all fixed allocations has been granted.
- **Best Effort Allocation (BEA):** This allocation is given after allocations have been made for the FA and the DA. The allocation is given to the operator without no guarantees and it is based strictly on the availability of the spectrum.

4.4.2.4 Spectrum allocation based on FFT and Bandwidth Mapping

As earlier mentioned in Section 2.4.4 of this thesis, the IEEE 802.16e standard uses S-OFDMA in sharing its PHY resources in order to apportion a wide range of channel bandwidths and spectrum. In accordance with this standard, the number of subcarriers used in the allocation of spectrum and bandwidth for the virtual network operators are appropriately mapped to match

the range of FFT and bandwidth sizes as expressed in the IEEE 802.16e S-OFDMA parameters shown earlier in Table 2.3. The mapping is done to ensure that the number of subcarriers allocated (whether their contracts are FA, DA or BEA) to each virtual base-station fits into the nearest FFT size and bandwidth as specified in the S-OFDMA parameters. Before the mapping process begins either for the FFT or Bandwidth (BW) mapping, the base-station with the FA SLA contract is first of all assigned spectrum in-line with the S-OFDMA parameters. Thereafter, the mapping algorithm is applied for the base-stations with SLA-contracts DA and BEA. The bandwidth and sub-carrier sizes are manipulated in OPNET through the OPNET WiMAX PHY Profile data structure (See **Appendix B**).

Figure 4.9 illustrates the FFT Mapping function (FFTMap) flowchart and the stages of its operation are explained as follows:

- The *FFTMap* function algorithm accepts two FFT/subcarrier values, one of which is the value that requires mapping (*fftInteger*) and the second value is the available spectrum in subcarriers (*AvailSpectrum*).
- After receiving these two values, the algorithm compares the *fftInteger* value with the *AvailSpectrum* value to first of all see if it falls within the upper value range (i.e. above 512 but less than the total subcarrier size of 2048). This is necessary because the available spectrum *AvailSpectrum* is obtained after the base-station with an FA contract has been allocated spectrum. If the *fftInteger* falls within this range, it will be assigned an FFT mapping value of 1024. The function *wimax_phy_support_fft_size_index_get* in OPNET sets this FFT index range in OPNET (see **Appendix C**).
- If the *fftInteger* does not fall into the upper range, it is then compared to see if it falls within the range of 128 – 512 subcarriers. If it falls within the range, an FFT mapping with the value 512 is assigned.
- A final range check of between 0 – 128 subcarriers is done if the *fftInteger* value does not fall within previous range. If the range 0 – 128 subcarriers is satisfied, an FFT mapping of 128 is assigned to the base-station.
- Finally, the function returns the mapped FFT (*mappedFFT*) value to the virtual spectrum allocation algorithm shown in Figure 4.13.

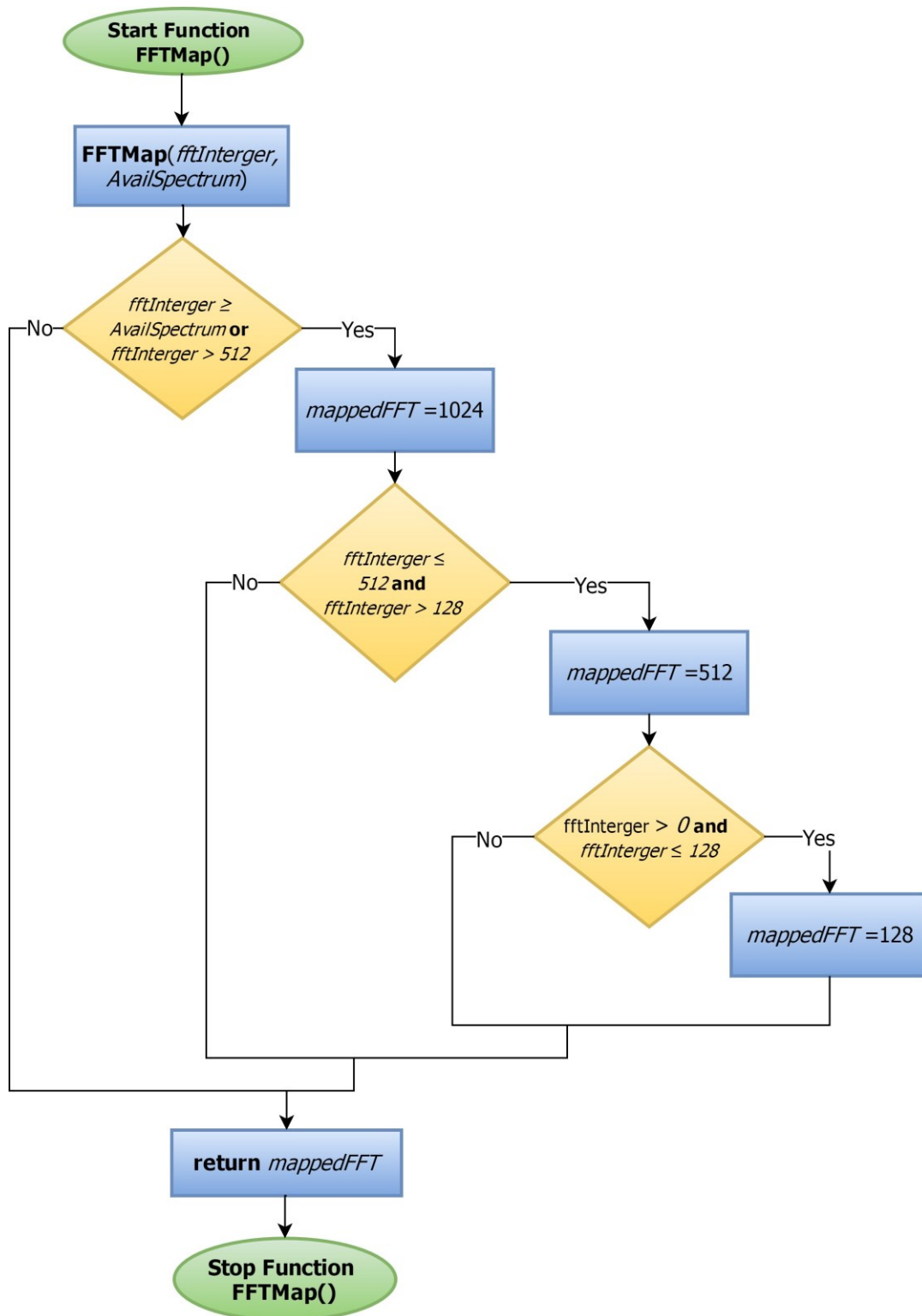


Figure 4.9 FFT Mapping Flowchart.

A similar operation to the FFT mapping takes place for the BW mapping process, as depicted in the flowchart shown in Figure 4.11. The flowchart defines the bandwidth mapping function (*BWMap*) algorithm and its operational stages are outlined as follows:

- The *BWMap* function accepts two FFT/Subcarriers values (*fftInterger* and *AvailSpectrum*) and in similar fashion to *FFTMap* algorithm, it maps the appropriate bandwidth value corresponding to the FFT/subcarrier size.
- If the FFT/subcarrier size falls within the upper value range which is above 512 but less than the total subcarrier size of 2048, the bandwidth mapping algorithm will assign a bandwidth of 10.0 (which is in MHz).
- Subsequently, if the *fftInterger* does not fall into the upper range, as was the case in the *FFTMap* algorithm, the *fftInterger* value is then compared to see if it falls within the range of 128 – 512 subcarriers. If it falls within this range, a bandwidth mapping of 5.0 is assigned.
- Again a final range check of between 0 – 128 subcarriers is done and if the *fftInterger* value does not fall within the previous range but satisfies this current range, a bandwidth mapping of 1.25 is assigned to the base-station.
- At the final stage, the function returns the mapped bandwidth (*mappedBW*) value to the virtual spectrum allocation algorithm shown in Figure 4.13.

The OPNET implementation of the algorithms for function *FFTMap* and *BWMap* is performed by a single function *wimax_vs_bw_estimation_calc()* and this function is triggered when an FA SLA contract allocation is initiated. A snippet of the code showing when the function is called is depicted in Figure 4.10 below:

```
// Calling the wimax_vs_bw_estimation_calc() function
if(my_mac_address == 2)
{
    wimax_vs_bw_estimation_calc(BW_Req);
    subcarrier_holder_desc_two = phy_profile_ptr->num_subcarriers;
}
```

Figure 4.10 FFTMap and BWMap Function call in OPNET.

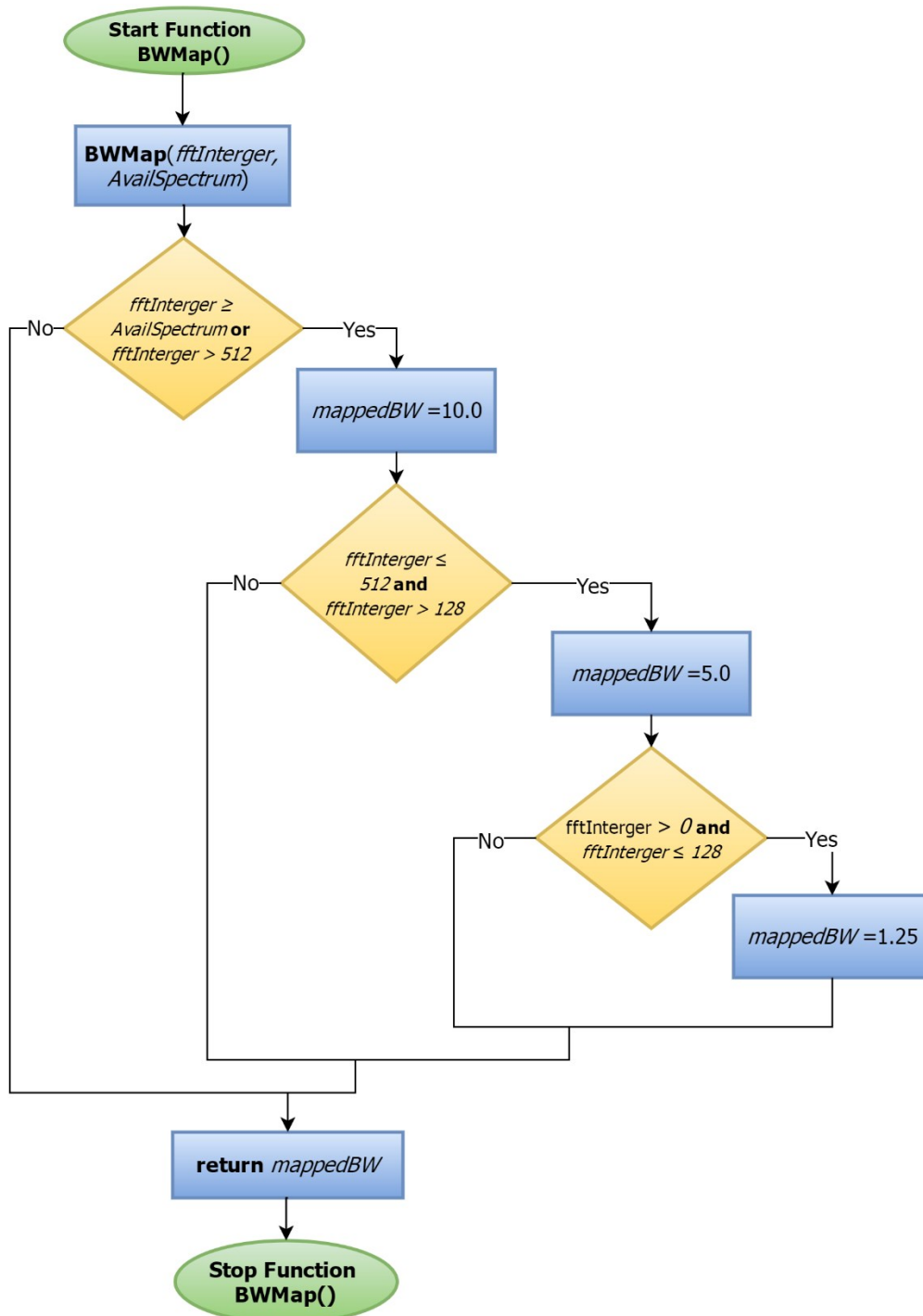


Figure 4.11 Bandwidth Mapping Algorithm.

The Figure 4.12 shows a snippet of the proto-c code that implements the FFT and bandwidth (BW) mapping algorithms in OPNET.

```

//FFT Mapping and BW Mapping for DA Contract
FIN(wimax_vs_bw_estimation_calc());

if((total_frame_subcarriers >= avail_spectm)|| (total_frame_subcarriers > 512))
{
    BS_Subcarriers_2 = 1024;
    BS_BW_2 = 10.0;
}
else if ((total_frame_subcarriers <= 512) && (total_frame_subcarriers > 128))
{
    BS_Subcarriers_2 = 512;
    BS_BW_2 = 5.0;
}
else if((total_frame_subcarriers > 0) && (total_frame_subcarriers <= 128))
{
    BS_Subcarriers_2 = 128;
    BS_BW_2 = 1.25;
}
else
{
    //do nothing
}

```

```

//FFT Mapping and BW Mapping for BEA Contract
avail_spectm = avail_spectm - BS_Subcarriers_2;

if((avail_spectm >= 1536)|| (avail_spectm > 512))
{
    BS_Subcarriers_3 = 1024;
    BS_BW_3 = 10.0;
}
else if ((avail_spectm <= 512) && (avail_spectm > 128))
{
    BS_Subcarriers_3 = 512;
    BS_BW_3 = 5.0;
}
else if((avail_spectm > 0) && (avail_spectm <= 128))
{
    BS_Subcarriers_3 = 128;
    BS_BW_3 = 1.25;
}
else
{
    BS_Subcarriers_3 = 128;
    BS_BW_3 = 1.25;
}

```

Figure 4.12 FFT & BW Mapping Code in OPNET.

The algorithm used for virtual spectrum allocation by the VS-Hypervisor is shown the flowchart illustrated in Figure 4.13. This algorithm in OPNET implementation, precedes the FFT and BW mapping algorithms in the function-calling hierarchy. An outline of its operation is described as follows:

- The spectrum allocation algorithm accepts three inputs which includes: the contract type (*contractType*), the fixed spectrum allocation (*fixedSpecAlloc*) and the fixed bandwidth allocation (*fixedSpecBW*).
- Next, it initializes the maximum FFT/subcarrier (*MAXfft*) available to the entire physical base-station which in this case is 2048 as defined by the IEEE802.16e standard.
- Using the contract type categories, it first of all allocates spectrum to the virtual network operator or base-station whose contract type is FA. The spectrum and bandwidth allocation of the SLA contract in this category is the *fixedSpecAlloc* and *fixedBWAlloc* respectively. After that the available spectrum is re-calculated (*AvailSpectrum*).
- Following that, the algorithm checks if contract type is DA and if the answer is true, the spectrum and bandwidth allocation will be the FFT and BW mapping of the estimated spectrum (ES_{total}) respectively.
- After that step is completed, the algorithm re-calculates the available spectrum again by subtracting the FFT mapped (ES_{total}) from the previous available spectrum value. The spectrum that is left (*SpecAllocleft*), is initialized to the newly re-calculated available spectrum.
- Finally, the VS-Hypervisor allocates for contract type BEA by using whatever is left of the spectrum (*SpecAllocleft*). Once again, FFT and BW mapping is performed on this value.

Spectrum allocation will not be granted to any additional operator if its request exceeds what is available on the physical infrastructure.

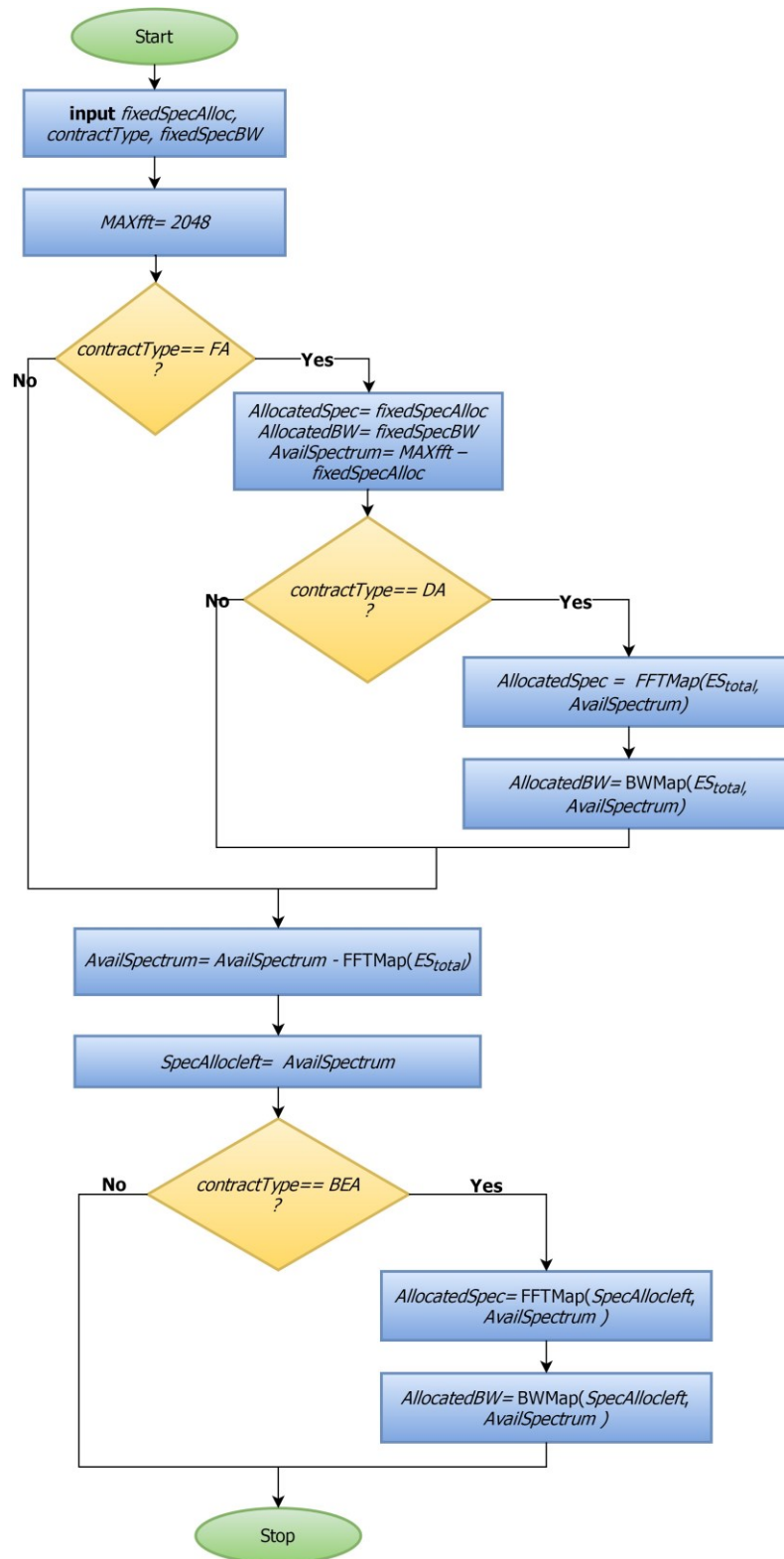


Figure 4.13 Spectrum Allocation Algorithm.

The proto-c code snippets shown in Figure 4.14, Figure 4.15 and Figure 4.16 illustrate the spectrum allocation for FA, DA and DEA SLA contracts as implemented on OPNET.

```

/*for Contract FA (Fixed Allocation) */
if(BASE_Station_MAC==1)
{
    num_alloc_spectrum_bs_1 = op_stat_reg("VS Hypervisor.Allocated subcarriers BS 1", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(num_alloc_spectrum_bs_1, sthandl_BS_Subcarriers_1);

    bw_alloc_bs_1 = op_stat_reg("VS Hypervisor.Allocated Bandwidth BS 1 (MHz)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(bw_alloc_bs_1, (bw_stathandl_1));
}

```

Figure 4.14 Spectrum and Bandwidth Allocation for FA Contract in OPNET.

```

/*for Contract DA (Dynamic Allocation) */
if(BASE_Station_MAC ==2)
{
    num_alloc_spectrum_bs_2 = op_stat_reg("VS Hypervisor.Allocated Spectrum in Base Station 2 (MHz/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(num_alloc_spectrum_bs_2, (sthandl_BS_Subcarriers_2));

    bw_alloc_bs_2 = op_stat_reg("VS Hypervisor.Allocated Bandwidth BS 2 (MHz)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(bw_alloc_bs_2, (bw_stathandl_2));
}

```

Figure 4.15 Spectrum and Bandwidth Allocation for DA Contract in OPNET.

```

/*for Contract BEA Best Effort Allocation) */
if(BASE_Station_MAC ==3)
{
    num_alloc_spectrum_bs_3 = op_stat_reg("VS Hypervisor.Allocated Spectrum in Base Station 3 (MHz/sec)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(num_alloc_spectrum_bs_3, (sthandl_BS_Subcarriers_3));

    bw_alloc_bs_3 = op_stat_reg("VS Hypervisor.Allocated Bandwidth BS 3 (MHz)", OPC_STAT_INDEX_NONE, OPC_STAT_LOCAL);
    op_stat_write(bw_alloc_bs_3, (bw_stathandl_3));
}

```

Figure 4.16 Spectrum and Bandwidth Allocation for BEA Contract in OPNET.

4.4.2.5 VS-Hypervisor Operational Characterization

Within this research, the operational characteristics of the VS-Hypervisor is described [84] considering that it constantly receives spectrum requests from multiple VNOs. One important operational characteristic to consider is how long it takes (time delay) for the VS-Hypervisor to process a spectrum request. Let the time delay be denoted as T_i and let the demand or request for spectrum/bandwidth (BW) by each VNO_i be represented as $D_i(t)$ for an instance of time t , whereby the VS-Hypervisor receives this requests simultaneously from the various VNOs. Bearing in mind these factors, the response of the VS-Hypervisor after a request can be denoted as $Y_i(t)$ which is for a granted request without any time delay from the VS-Hypervisor. Such can only happen in an ideal situation, whereas for a real situation, the response time for the VS-Hypervisor will be represented as $Y_i(t - T_i)$ as shown in Figure 4.17 below:

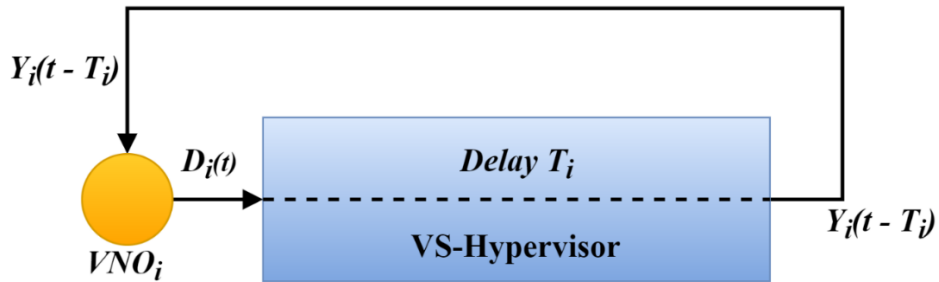


Figure 4.17 VS-Hypervisor Time Delay Block.

The VS-Hypervisor input signal $D_i(t)$ can be represented using the diagram shown in Figure 4.18.

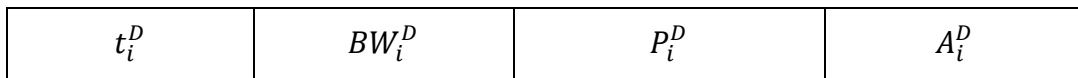


Figure 4.18 VS-Hypervisor Input Information.

Where t_i^D is the time at which the request $D_i(t)$ is dispensed, BW_i^D is the aggregate bandwidth that is requested or demanded by the VNO_i at time t_i , the current priority/rank P_i^D of VNO_i in terms of bandwidth allocation and A_i^D is the antecedent priority/rank of VNO_i with regards to

BW allocation in the previous allocation cycle of the VS-Hypervisor. The output signal $Y_i(t)$ has the following structure expressed in Figure 4.19 below:

t_i^A	BW_i^A	P_i^A	F_i^A	T_i^A	S_i^A	E_i^A
---------	----------	---------	---------	---------	---------	---------

Figure 4.19 VS-Hypervisor Output Information.

Where t_i^A is the time stamp at which the allocation $Y_i(t)$ is issued, BW_i^A is the amount of bandwidth/spectrum that is allocated by the VS-Hypervisor to VNO_i , P_i^A is the priority/rank of VNO_i in the next cycle of spectrum allocation by the VS-Hypervisor, F_i^A is the frequency plan (that is, the indexes of frequency channels to be used in the next allocation cycle to implement BW_i^A), T_i^A is the time plan (that is, the indexes of OFDMA symbols to be used in the next allocation cycle to implement BW_i^A), S_i^A represents the start time of the next allocation cycle of BW (spectrum) addressing the VNO_i demand being processed and E_i^A is the end time of the next allocation cycle of BW addressing the current VNO_i demand. Figure 4.20 shows the time-flow of the VS-Hypervisor. Where $(t_i^D, BW_i^D, P_i^D, A_i^D) \in t_i^D$.

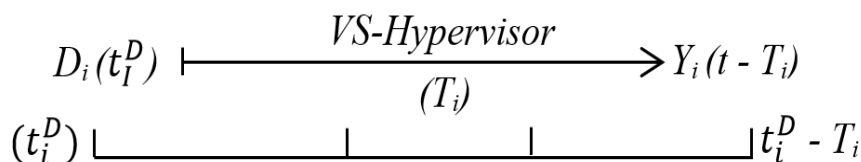


Figure 4.20 VS-Hypervisor Time-Flow Structure.

Alternatively, the VS-Hypervisor Time-flow structure can be better expressed in equation (4.2) below:

$$Y_i(t_i^D - T_i) = \begin{cases} NULL, & \text{if } t_i^D - T_i \leq 0 \\ H_i[D_i(t_i^D)], & \text{if } t_i^D - T_i > 0 \end{cases} \quad (4.2)$$

Where $H_i[D_i(t_i^D)]$ is the VS-Hypervisor's input/output mapping function characterization corresponding to the each VNO_i represented in Figure 4.21.

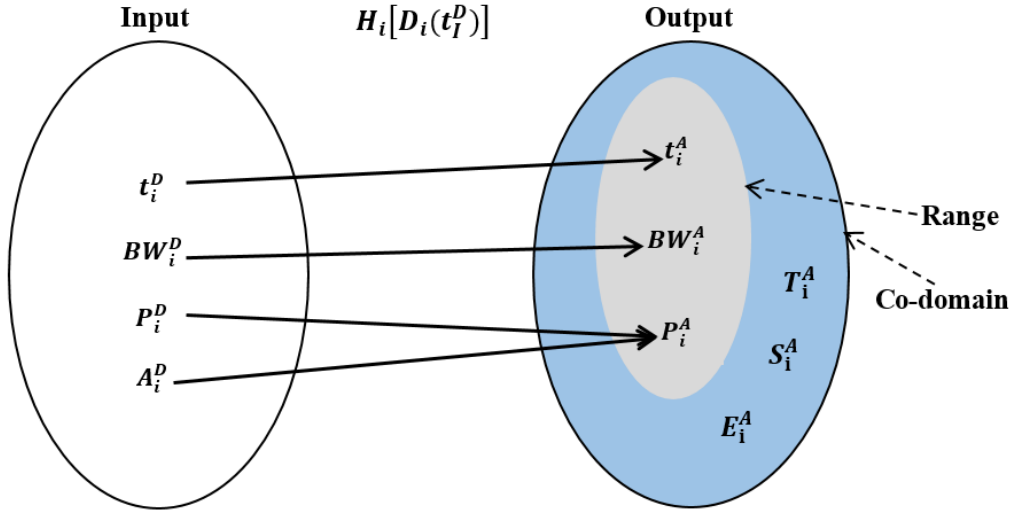


Figure 4.21 VS-Hypervisor Input/output Mapping.

Where the remaining outputs T_i^A , S_i^A and E_i^A from Figure 4.19 are part of the co-domain of the function $H_i[D_i(t_i^D)]$ as shown in Figure 4.21. They represent the time variables for the next cycle of spectrum/bandwidth allocations (as previously explained). The definition of the mapping function $H_i[D_i(t_i^D)]$ can be further expressed using the equation (4.3) in relation to its range.

$$H_i[D_i(t_i^D)] = \{(t_i^D, t_i^A), (BW_i^D, BW_i^A), (P_i^D, P_i^A), (A_i^D, P_i^A)\} \quad (4.3)$$

Fundamentally, the mapping function $H_i[D_i(t)]$ is controlled by a state machine in the VS-Hypervisor's process model (section 3.5.2.1) containing external events $D_i(t)$, having an internal state evolution subject to system capability functionality constraints which can be expressed using equation (4.4).

$$BW_1^D + BW_2^D + \dots + BW_n^D \leq C \quad (4.4)$$

Equation (4.4) is the sum of BW/spectrum requested by the VNOs which cannot exceed system capacity C and this factor constitutes the major constraint of the spectrum virtualization framework. This operation of this equation is carried out by the subcarriers estimation unit within each VNO; whereby the estimated subcarriers are then mapped with the approximate bandwidth size as represented in Figure 4.7 and described in Section 4.4.2.4.

4.5 Performance Analysis of WiMAX Spectrum Virtualization

In this section, a performance analysis for WiMAX spectrum virtualization is carried out to assess its capability and to ascertain if it meets the minimum network performance for a varied number of services. To achieve this, a WiMAX Spectrum virtualization simulation model is setup in the OPNET Modeler as shown in Figure 4.22.

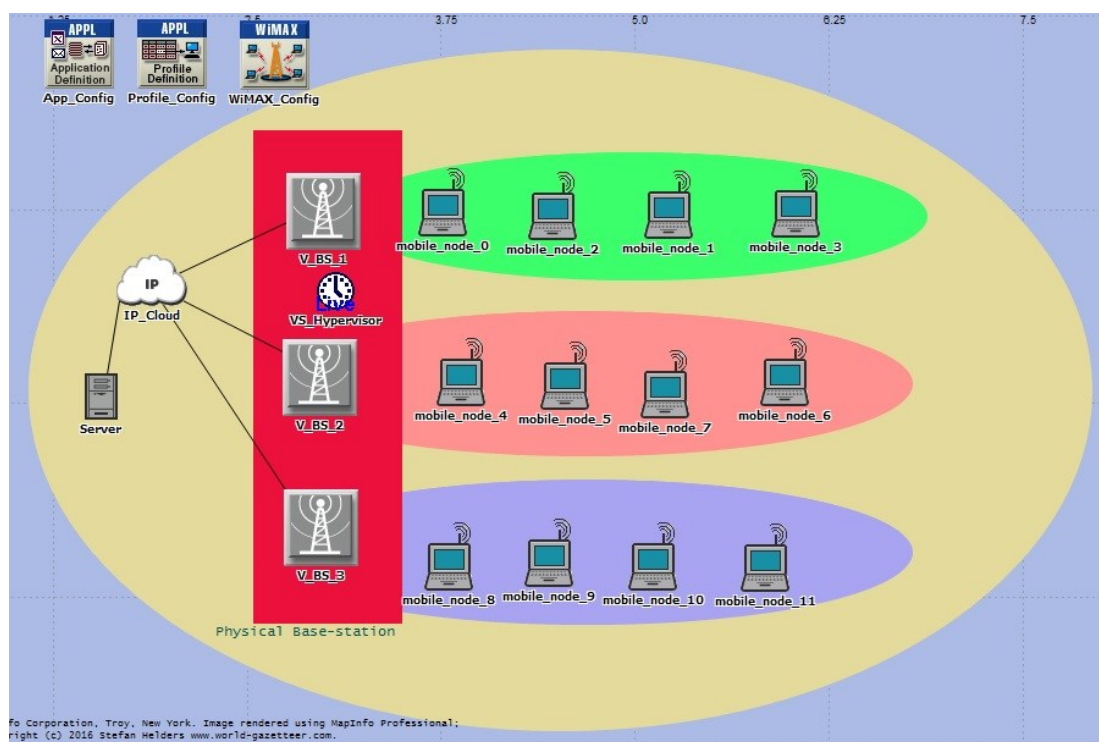


Figure 4.22 WiMAX Spectrum Virtualization Model.

From the Figure 4.22, there are three virtual base-stations (V_BS_1 , V_BS_2 & V_BS_3), all sharing the same physical base-station infrastructure and they are connected to an IP cloud network which is connected to a server that provides various services.

The VS-Hypervisor node is also shown in Figure 4.22 and it is responsible for the virtualization of the wireless spectrum. As stated earlier, this research work does not focus on the virtualization of the physical WiMAX base-station network but on the spectrum. A virtualized physical base-station which supports full-duplex transmission is assumed.

To discover the benefits and the advantages of spectrum virtualization, this research compares the *virtualized* WiMAX base-station network where spectrum is shared to a *non-virtualized* WiMAX base-station network and two major scenarios are investigated:

- The sharing of the wireless spectrum between the VNOs by the VS-Hypervisor based on the SLA-contracts described earlier.
- The performance of the virtual base-stations based on throughput and end-to-end delay. When considering throughput and delay, it is important to know if the virtualized base-stations meet the minimal data rates and delay for various traffic services such as voice, video and data. Table 4.3 shows samples of traffic parameters for broadband wireless applications [30].

Table 4.3 Broadband Wireless Applications Traffic Parameters (from [30]).

Parameter	Voice	Streaming Media	Video	Data
Data Rates	4Kbps – 64Kbps	5Kbps– 384Kbps	> 1Mbps	0.01Mbps– 100Mbps
Application Examples	VoIP	Music, speech, video clips	Video Streaming	Web Browsing
Traffic Flow	Real-time continuous	Continuous, bursty	Continuous	Non-real time, bursty
Delay	< 100 ms	< 250 ms	< 100 ms	Flexible

4.5.1 SLA Contract Based Analysis

This scenario is setup to know how the wireless spectrum is shared amongst the WiMAX base-stations. The scenario is simulated using the same traffic for all the virtual base-stations (VB). The parameter configuration for the scenario is described in Table 4.4.

Table 4.4 Simulation Parameters & Configuration for SLA Contract Analysis.

Parameters	Configuration
Number of Virtual Base-stations	Three (3)
Circular Cell Radius	500 meters
Total Number of FFT & Subcarriers (Spectrum)	2048 subcarriers to be shared by the virtual base-stations
Total amount of Bandwidth	20MHz
Frequency Band	5GHz
Duplexing Technique	TDD
Permutation Scheme	PUSC
Virtualized Network Scenario	VB 1, VB 2 & VB 3 Share the 2048 subcarriers and the 20MHz Bandwidth
Number of subscriber stations	VB 1: 10 VB 2: 10 VB 3: 20
Contract Configuration	VB1: Fixed Allocation of 512 subcarriers VB2: Dynamic Allocation with a maximum of 1024subcarriers VB3: Best Effort Allocation
Traffic Configuration	Data: Web Browsing with multimedia
Simulation run time	600 seconds

Based on the simulation carried out using the configurations shown in Table 4.4, Figure 4.23 shows the number of spectrum (subcarriers) allocated to each virtual base-station dependent on their individual SLA contracts while Figure 4.24 shows the number of subcarriers utilized per virtual base-station after spectrum has been allocated.

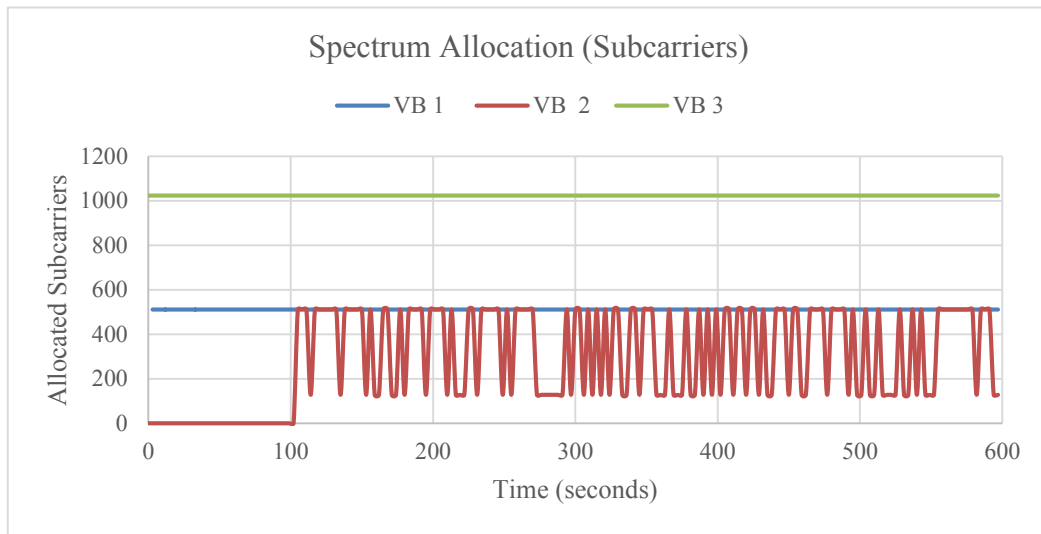


Figure 4.23 Spectrum Allocation per Virtual Base-station.

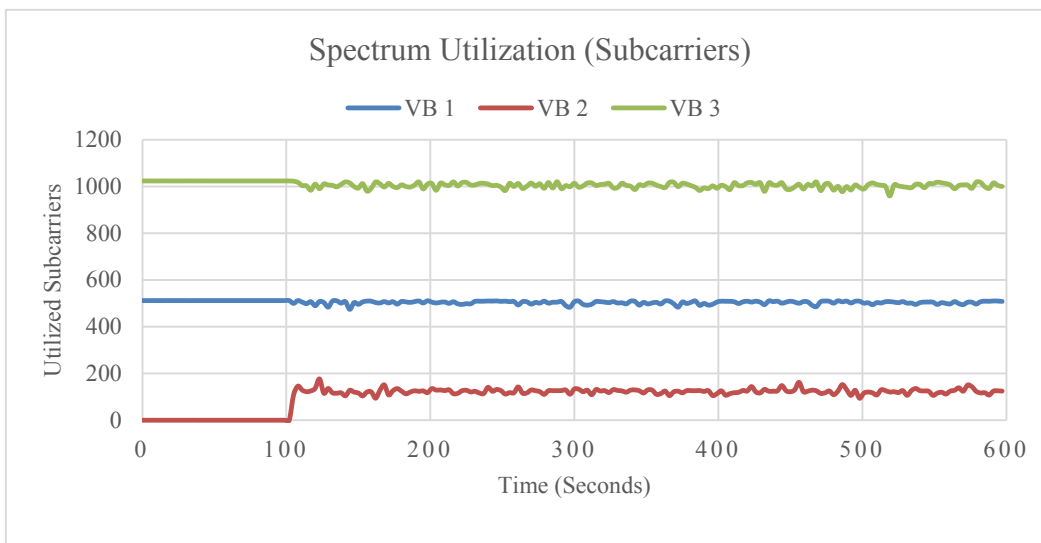


Figure 4.24 Spectrum Utilization per Virtual Base-station.

In Figure 4.23, it can be seen that VB 1 has a steady allocation of 512 subcarriers because of its SLA-contract (FA) which guarantees a fixed allocation of spectrum. VB 2, shows a fluctuating allocation of spectrum because its SLA-contract (DA) guarantees that spectrum is allocated to it based on its need per time. This Ping-Pong like allocation is also attributable to the traffic type configured inside VB 1 (which in this scenario is a combination of web browsing, data traffic and multimedia traffic). The result clearly shows that when there is an

increase in spectrum demand from the subscribers of VB 2, the VS-Hypervisor uses the demanded subcarriers estimate received from VB 2 to map onto an appropriate FFT size (spectrum size); which in this scenario never exceeded 512 subcarriers. VB 3 shows a steady allocation of spectrum at 1024 subcarriers which is a lot higher than VB 2 considering that VB 3 is on a best-effort SLA-contract (BEA). The high allocation for VB 3 is as a result of the lesser demand for spectrum made by VB 2 to the VS-Hypervisor which did not exceed 512 subcarriers. Since VB 1 had a fixed allocation of 512 subcarriers, and VB 2 did not demand more than 512 subcarriers, this meant that 1024 subcarriers was still be available for allocation to VB 3 based on the FFT mapping algorithm explained earlier in Section 4.4.2.4.

In Figure 4.24, it can be seen that the utilized subcarriers varies below the allocated spectrum for VB 1 and VB 3. Whereas in VB 2, the utilized subcarriers appears to exceed its initial spectrum allocation (128 subcarriers) but does not peak at its maximum allocation (512 subcarriers). This can be attributed to the channel bandwidth demand made to it by its subscribers or mobile stations. If the utilized subcarriers for all the virtual base-stations are stacked using a bar-chart as shown in Figure 4.25, an overall view of the spectrum utilization is illustrated.

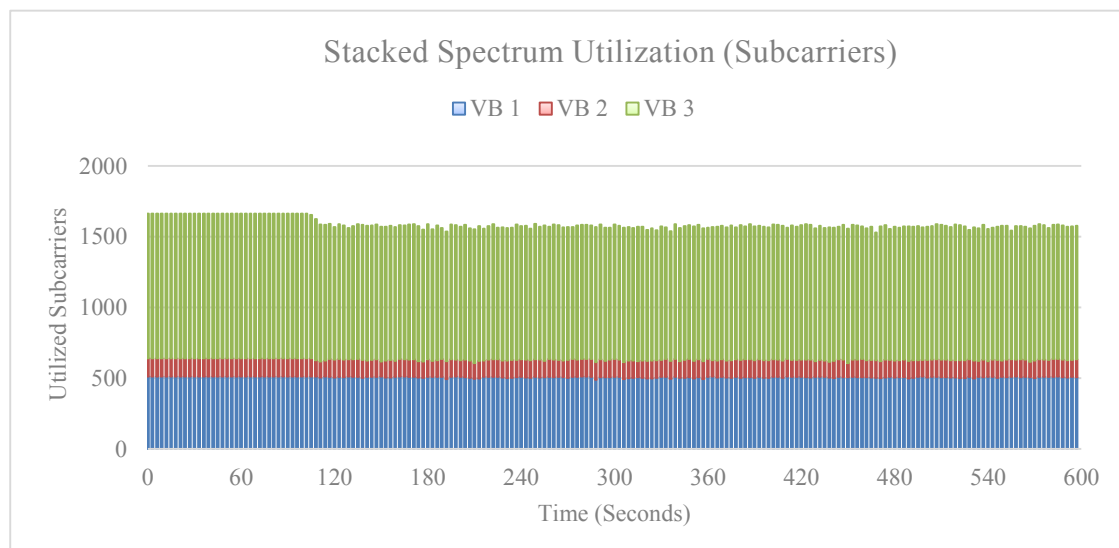


Figure 4.25 Overall Spectrum Utilization.

An in-depth observation of Figure 4.25 shows that not all of the entire spectrum (2048 subcarriers) available on the physical base-station was utilized even though the spectrum was shared by three virtual base-stations. A significant amount of spectrum was still available for further allocation. This attests to the effectiveness of the VS-Hypervisor in scheduling the spectrum resource and it also demonstrates the advantage of *Spectrum Virtualization* as a reliable method for efficient spectrum sharing and utilization.

The Figure 4.26 shows the average bandwidth utilization for VB1, VB2 and VB3; which is calculated using OPNET's built-in averaging statistical tool. It illustrates that VB2 has utilized more bandwidth channels than its initial bandwidth allocation because of the Ping-Pong like (dynamic) spectrum allocation given to it by the VS-Hypervisor which is also as a result of the bandwidth demand placed on it by its subscribers.

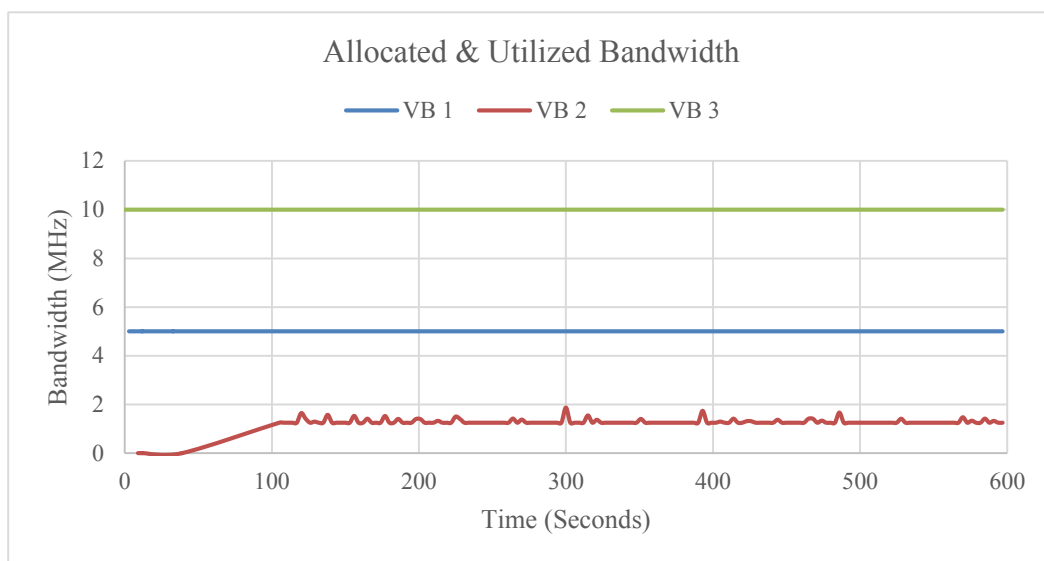


Figure 4.26 Average Utilized Bandwidth per Virtual Base-station.

4.5.2 Traffic Based Analysis and Results

This section analyses the performance of a physical base-station possessing spectrum virtualization capability in comparison with a non-virtualized base-station when different traffic which includes data (web browsing), video (video streaming) and voice (VoIP) are

deployed. The simulation is done for varied number of users to test for throughput and delay. Table 4.5 shows the simulation scenario parameters.

Table 4.5 Simulation Parameters & Configuration for Traffic Based Analysis.

Parameters	Configuration
Number of Virtual Base-stations in virtualized physical base-station	Three (3)
Number of non-virtualized Base-stations	Three (3)
Circular Cell Radius	500 meters
Total Number of FFT & Subcarriers (Spectrum)	2048
Total amount of Bandwidth	20MHz
Frequency Band	5GHz
Duplexing Technique	TDD
Permutation Scheme	PUSC
Virtualized Network Scenario	VB 1, VB 2 & VB 3 Share the 2048 subcarriers and the 20MHz Bandwidth
Non-virtualized Network Scenario	All three base-stations have 2048 subcarriers and 20MHz bandwidth independently
Number of Subscriber Stations	Simulated for 5, 10, 15, 20 & 30 subscriber stations per virtual base-station and physical base-stations in the non-virtualized setup
Contract Configuration for Virtualization	VB1: Fixed Allocation of 512 subcarriers VB2: Dynamic Allocation with a maximum of 1024subcarriers VB3: Best Effort Allocation
Traffic Configuration	VB 1: Voice (VoIP Telephony) VB 2: Video (video streaming) VB 3: Data (Web browsing) The physical base-stations 1, 2 & 3 are configured in similar manner.
Simulation run time	20 minutes (1200 seconds)

After performing the simulations for the parameters presented in Table 4.5, the results gotten for each traffic category is explained in the subsequent sub-sections.

4.5.2.1 Voice Traffic Configuration in OPNET

This Section explains the OPNET configuration settings for the voice traffic deployed on VB1 as well the corresponding non-virtualized base-station. The configuration is done using the Application Definition node in OPNET. The voice configuration sets up IP Telephony as shown in Figure 4.27 and its key attributes are described as follows:

- **Silence Length (seconds):** This attribute defines the period of silence during a conversation for in-bound and out-bound traffic streams. The default setting is 0.65 seconds which is a mean outcome of an exponential distribution [85].
- **Talk Spurt Length (seconds):** This attribute describes the lengths of uninterrupted talk periods during a conversation period. If is given a default setting of 0.352seconds and it is also a mean outcome of an exponential distribution [85].
- **Symbolic Destination Name:** This basically the symbolic for a destination node that partakes in the voice communication and in this case the symbolic destination name is set to Voice Destination.
- **Encoder Scheme:** This attribute specifies the algorithm used in encoding the voice information into a digital signal. In this case, the G.729A encoder. This encoder is specified by the ITU [86] for encoding speech at 8 Kbit/s and it is supported by the voice over Internet Protocol VoIP application.
- **Voice Frames per Packet:** This is the attribute that defines the number of encoded voice frames placed in a single packet as the data moves from the application layer to the lower layers [85].
- **Type of Service (ToS):** This attribute specifies the ToS field in the IP packet header and in the case it configured as an interactive voice service.
- **RSVP:** The Resource Reservation Protocol (RSVP) was not configured in this simulation.
- **Traffic Mix (%):** This expresses the mix of traffic during simulation. The All Discrete setting was configured i.e. all the voice data is modelled as only explicit traffic [85].

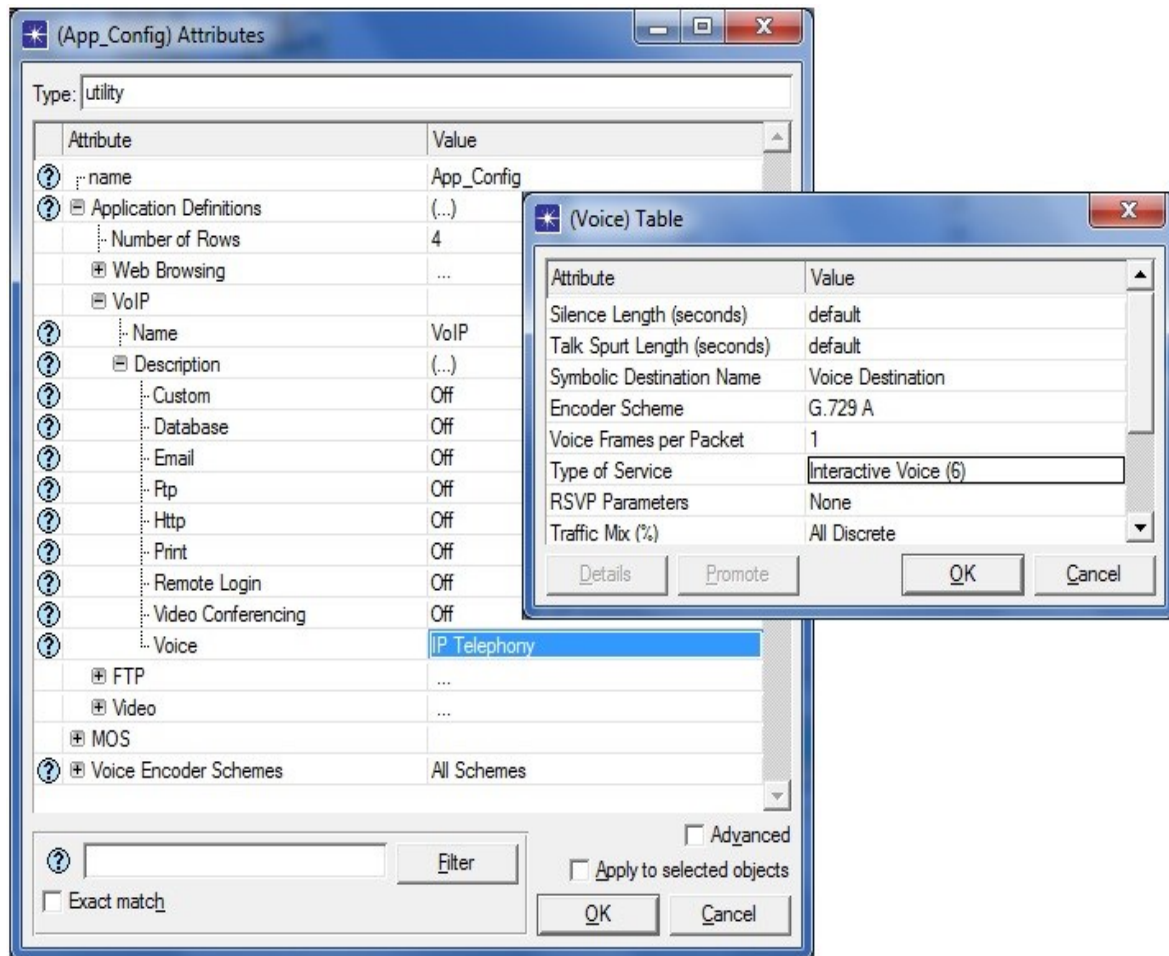


Figure 4.27 VB1 OPNET Voice Configuration.

4.5.2.2 Voice Traffic Result & Analysis

In this scenario, after the voice over IP (VoIP) application is configured in OPNET's application configuration node, the VoIP traffic is then sent over the virtual base-station VB1 whose SLA contract is a fixed allocation (FA) of spectrum/bandwidth (512 subcarriers at 10MHz bandwidth). The same VoIP traffic is also passed onto a non-virtualized base-station having full spectrum and bandwidth allocation (2048 subcarriers at 20MHz bandwidth). After the simulation process is completed, the results for throughput on both base-stations are obtained as shown in Figure 4.28. It can be seen that the throughput performances of the virtualized/non-virtualized base-stations are almost equal and closely similar despite the sharp

disparities in their spectrum allocations and spectral capacities. This can be attributed to the fact that the mobile WiMAX standard (IEEE 802.16e) specifies a minimum reserved data-rate for VoIP traffic based its QoS traffic definitions. This minimum reserved data-rate has clearly been satisfied by the virtualized/non-virtualized base-stations resulting in their very close performances in terms of throughput. Considering this finding, this proves that spectrum virtualization serves as a good mechanism for spectrum management, ensuring that physical base-station resources like—spectrum—which would have been wastefully utilized can now be optimally utilized through *sharing* via virtualization.

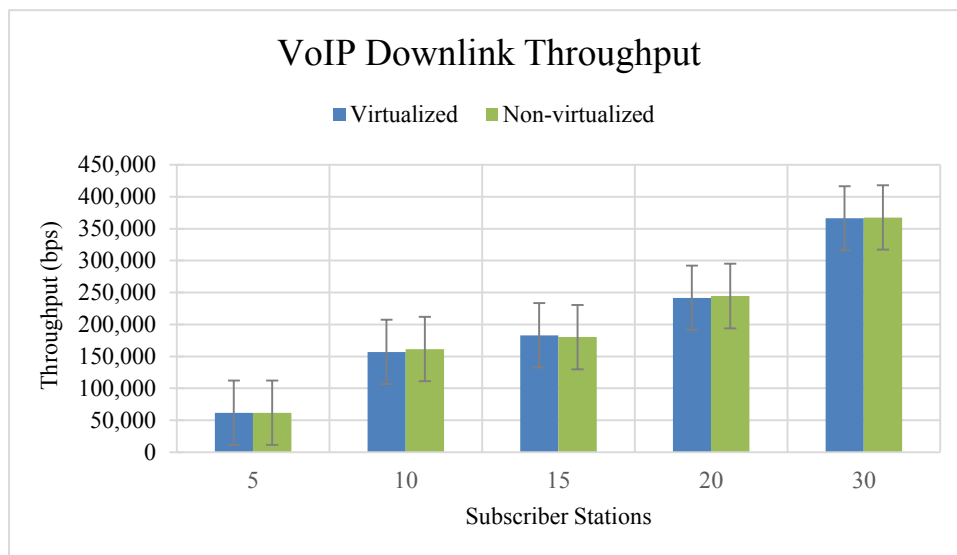


Figure 4.28 VB1 Average Voice (VoIP) Throughput.

The Figure 4.29 illustrates the average end-to-end delay for the VoIP application for both the virtualized and non-virtualized scenarios and it shows that the delay increases in a gradual manner with an increase in the number of subscriber stations. The increase in delay is a result of the number of subscriber stations waiting to have access to the OFDMA frequency-time channels of the individual virtual and non-virtualized base-stations to either transmit or receive packets. It can also be seen that there is no difference in the delay performance between the virtualized and the non-virtualized base-stations validated by the overlaps of the Standard Error (SE) bars.

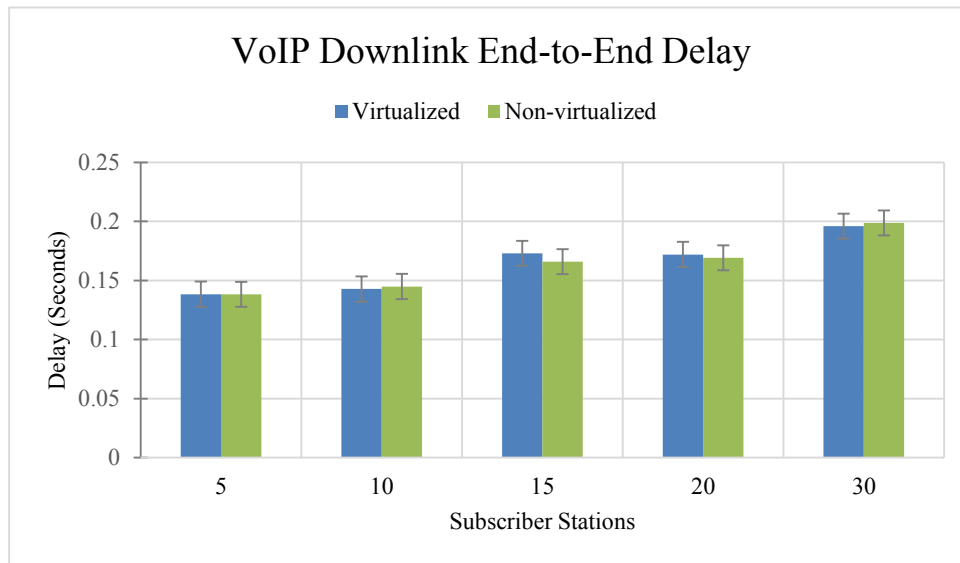


Figure 4.29 VB1 Voice (VoIP) Average End-to-End Delay.

4.5.2.3 Video Traffic Configuration in OPNET

The OPNET video traffic configuration (to be sent in VB2 and the corresponding non-virtualized base-station) is shown in Figure 4.30. Its attribute features are explained as follows:

- **Frame Interarrival Time Information:** This attribute specifies the frequency of video frame arrival for both incoming and outgoing traffic. In this simulation, the value is set at 15 frames/sec.
- **Frame Size Information (bytes):** It defines the size of each incoming and outgoing frame unit in bytes and in this simulation scenario the attribute value was set to 128 x 240 pixels. This is with an assumption that each pixel requires 9bits therefore a 128 x 240 pixel frame requires $128 \times 240 \times 9 \text{ bits} = 276,480 \text{ bits}$ which corresponds to 34,560 bytes.
- **Symbolic Destination Name:** The symbolic destination name for this simulation scenario is Video Destination.
- **Type of Service:** Best Effort is specified in the type-of-service packet header.
- **RSVP:** None
- **Traffic Mix:** The all discrete traffic mix setting is configured in this simulation scenario.

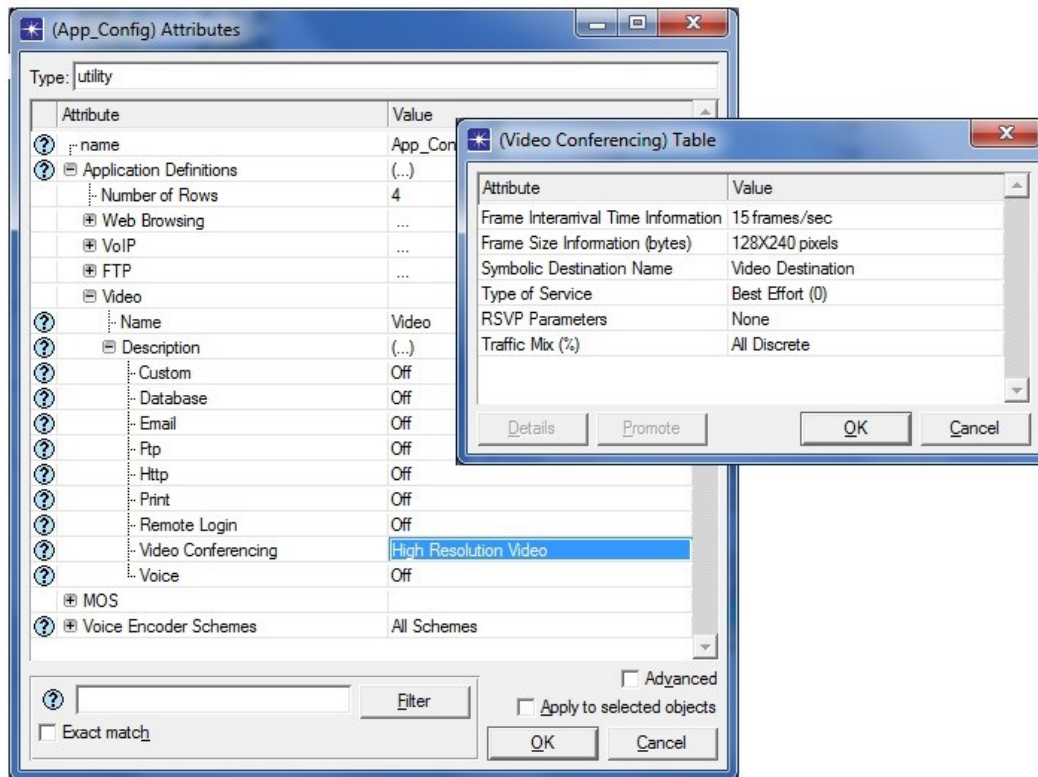


Figure 4.30 VB2 OPNET Video Traffic Configuration.

4.5.2.4 Video Traffic Result & Analysis

Video streaming traffic is configured on the virtual base-station—VB2, having also a dynamic allocation (DA) SLA contract configuration. A replica configuration of VB2 is implemented on a non-virtualized base-station, which has a full spectrum allocation analogous to the previous voice traffic scenario. The Figure 4.31, shows the average downlink throughput performance for both setups. The throughput performance for both setups are at par with the same varied number of subscribers. There is a steady decline in both of their throughput values—the resultant effect of a reduction in the capacity of the base-stations to meet the spectrum demands of their respective subscribers—for the video traffic. The significance of this result in relation to this research’s objectives, is that the virtualized base-station did not experience a diminished performance in its throughput compared with the non-virtualized base-station that had full spectrum allocation. This proves that the SLA DA contract of VB2 satisfied

its spectrum requirements hence its near-equal throughput performance with the non-virtualized base-station. The average end-to-end delay performance for both cases is illustrated in Figure 4.32.

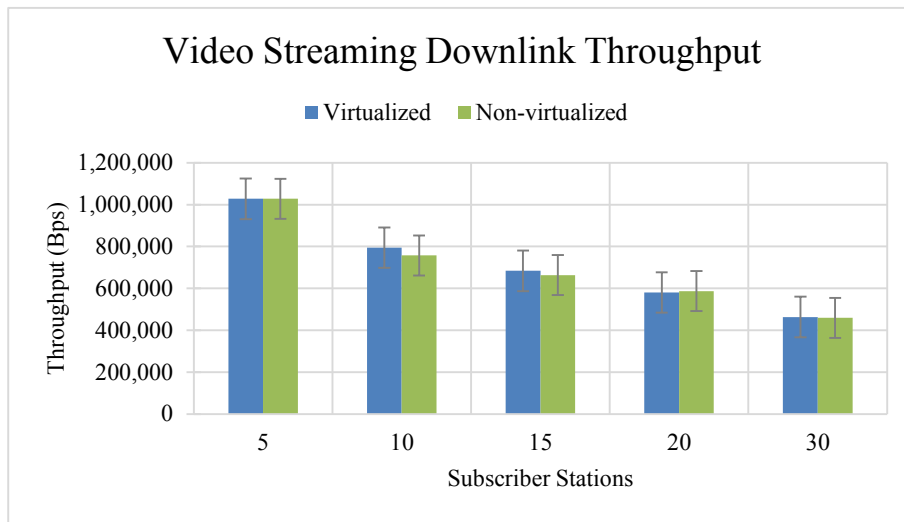


Figure 4.31 VB2 Video (Video Streaming) Average downlink Throughput

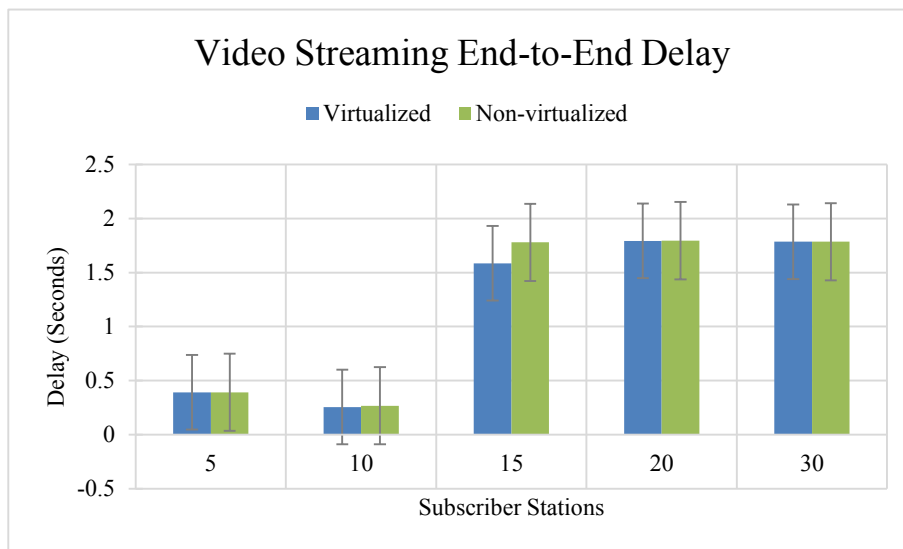


Figure 4.32 VB2 Video Streaming Average End-to-End delay

From the Figure 4.32, it can be seen that the average end-to-end delay rises, dips and steadies at a particular range of values as the number of subscriber stations increases and the virtual base-station's delay performance is at the same level at every instance with the non-virtualized

base-station. This is because of the dynamic allocation of spectrum by the VS-Hypervisor in spite of the non-virtualized base-station having more spectrum and bandwidth resources.

4.5.2.5 Data Traffic Configuration in OPNET

The OPNET configuration for web browsing data traffic for VB3 as well its equivalent non-virtualized base-station is shown in Figure 4.33 below:

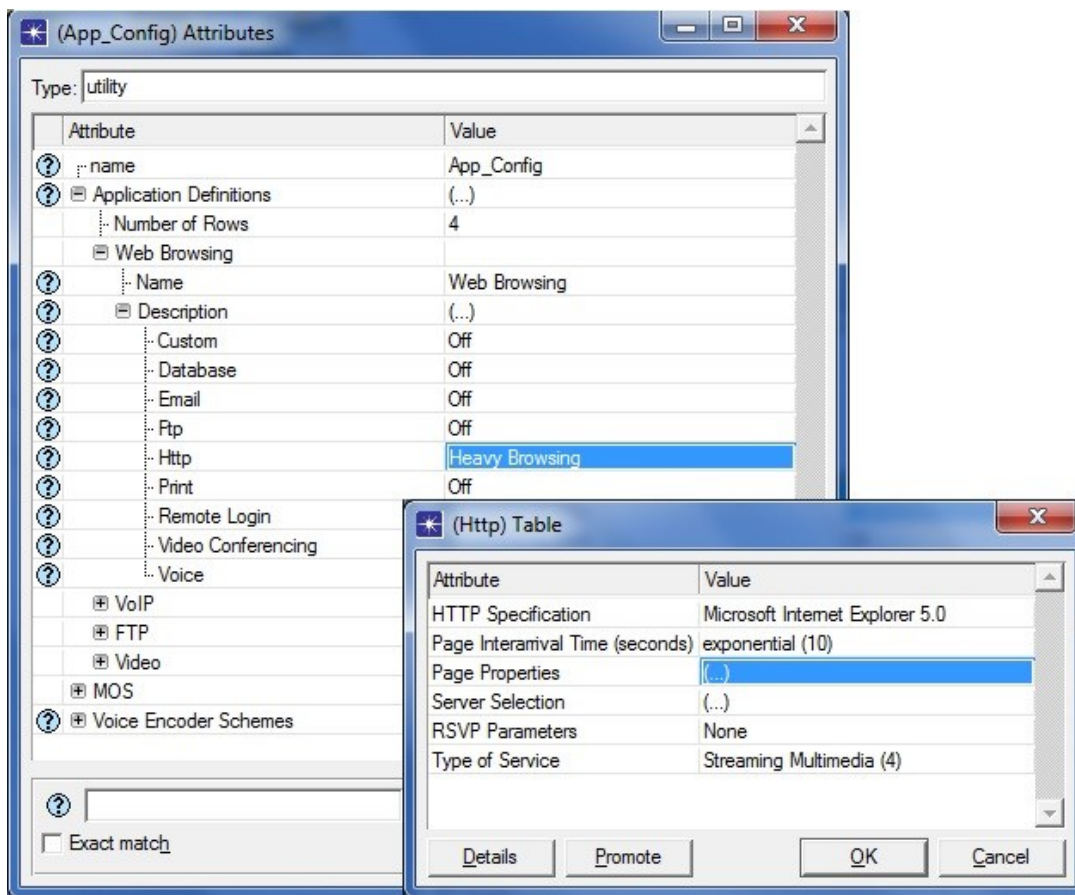


Figure 4.33 VB3 OPNET Web Browsing Data Traffic Configuration

The attribute features for the web-browsing data configuration are outlined as follows:

- HTTP Specification:** This attribute defines the Hypertext Transfer Protocol (HTTP) protocol used by the web browsers in the wireless subscriber stations in this simulation set-up. It also indicates the HTTP version being used which in this case is the version

5.0 and it is the highest version available in the OPNET Modeler 14.5 version used in this thesis.

- **Page Interarrival Time (seconds):** This attribute stipulates the time interval between successive web-page requests. It defines the behaviour of the user when browsing in terms of the amount of time it takes a user to review a web-page while browsing. In this scenario case, it was set 10 seconds.
- **Page properties:** The OPNET's representation of a web-page is described in this attribute. It defines the size of the file as well as the size of images in the files as shown in Figure 4.34. The **Object Size (bytes)** attributes specifies the size of a single object inside a web-page. The first row represent the Hypertext Markup Language (HTML) file size (1000 bytes) for a large image and the **number of objects** (number of images) configured in this scenario is 7. The **Location** attribute tells where the identifies the HTTP server location where the image resides and the Back-End Custom Application attribute defines applications to be used at the back-end but this is not specified in this scenario.

	Object Size (bytes)	Number of Objects (objects per page)	Location	Back-End Custom Application
constant (1000)	constant (1000)	constant (1)	HTTP Server	Not Used
Large Image	Large Image	constant (7)	HTTP Server	Not Used

Figure 4.34 OPNET HTTP Page Properties.

- **Server Selection:** This compound attribute determine if the embedded web-pages in a web-page will be open from the same server or from a different one. The attribute consists of two sub-attributes which are explained below and shown in Figure 4.35.

- **Initial Repeat Probability:** This sub-attribute defines the probability that embedded links when accessed for the first time are contained in the same server. In the settings for this scenario, a setting called *Research* is configured which determines a user's behaviour when carrying out a research work. The initial repeat Probability set for this case is 0.9.
- **Pages per Server:** Determines the number of web pages accessed consecutively from the same server.

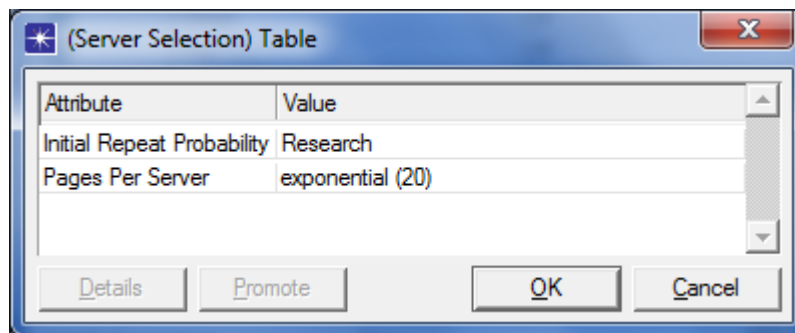


Figure 4.35 HTTP Server Selection Sub-attributes Configuration

- **RSVP Parameters:** In this scenario no RSVP setting was made.
- **Type of Service:** The streaming media service is configured as the type of service in this scenario.

4.5.2.6 Data Traffic Result and Analysis

Data traffic is an essential service in any wireless broadband network. In this scenario, the data traffic (web browsing with multimedia) is deployed in the virtual base-station VB3 which has a Best-effort SLA contract and also on its corresponding non-virtualized base-station. This is to test the performance of VB 3 when compared with a non-virtualized base-station which has full spectrum resources as described in the previous traffic cases. Figure 4.36 displays the web browsing downlink throughput result for both the virtualized and non-virtualized base-stations. The throughput appears to increase linearly as the number of users increases, similar to the voice scenario in Section 4.5.2.2 and this is also due to increase in the amount of data packets

both base-stations sent and received and the fact that more frequency channels were allocated to the subscriber stations due to the availability of spectrum on both the virtualized base-station and non-virtualized base-station. There is also difference in throughput output on both setups.

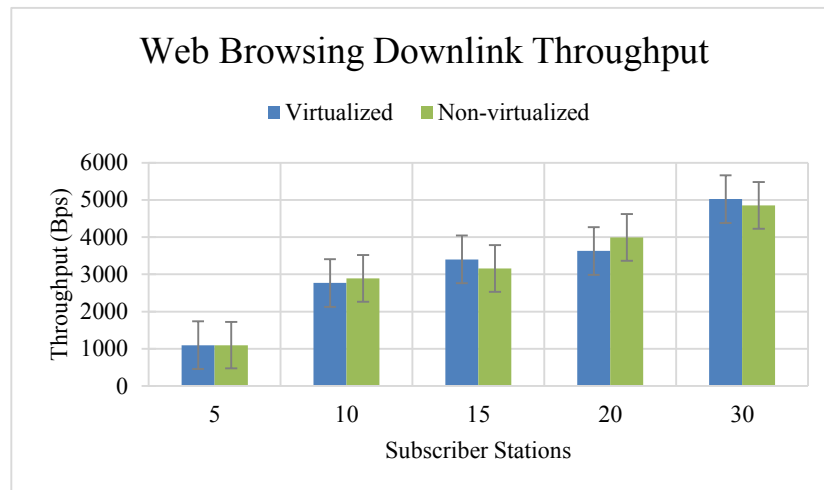


Figure 4.36 VB3 Average Data (Web browsing with multimedia) Downlink Throughput

Comparing the SE bars on both cases, overlaps can be seen which implies that the differences in their throughput outputs is not statistically significant. The average end-to-end delay performance for the web browsing traffic application on both the virtualized/non-virtualized base-stations as depicted in Figure 4.37 shows that the virtualized base-station VB has a lesser end-to-end delay as the number of subscriber stations increases when compared with the non-virtualized base-station. This is as a result of a delay in the allocation of bandwidth resources

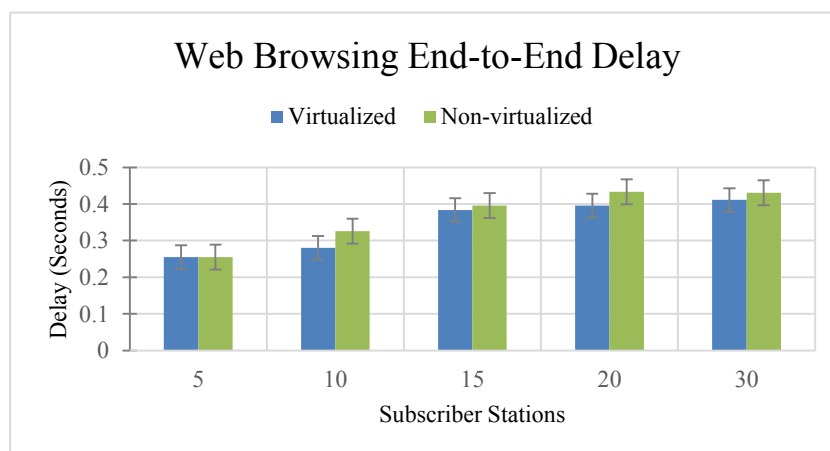


Figure 4.37 Average Web Browsing Downlink End-to-End Delay

by the individual MAC layers of the virtualized and non-virtualized base-stations. It is evident that there is statistical insignificance when the SE bars are compared for the end-to-end delay output for the base-station categories.

4.6 Conclusion

From the results gathered in the contract based analysis, it has been clearly established that spectrum virtualization is possible on a WiMAX network whereby a novel virtualization entity known as the VS-Hypervisor in a novel WiMAX Spectrum virtualization architecture splits, isolates and allocates the wireless spectrum for three virtual base-stations in accordance with S-OFDMA resource arrangement as defined by the mobile WiMAX standard. The results shows no sign of spectrum interference between the virtual base-stations and every base-station was allocated spectrum based on their individual SLA contracts. The result also shows that after spectrum has been allocated, there was an appreciable level of spectrum utilization by all the virtual base-stations leaving an extra amount of spectrum for further allocation. The results demonstrates that its possible for multiple VNOs to share a physical base-station spectrum resource which will contribute in the reduction of Capital Expenditure (CAPEX) and operational expenditure (OPEX) for new and existing WiMAX network operators since they do not need to their own physical infrastructure and it also opens up newer business opportunities.

Shifting attention to the traffic based analysis, the results shows that for the three traffic categories deployed (voice, video and data), the virtualized base-stations (VB1, VB2 & VB3) performed in like manner with the non-virtualized base-stations, albeit that they had lesser amount spectrum bandwidth resources. The voice throughput for VB1 stayed within the acceptable data rate range for wireless broadband technologies as specified in Table 4.3. The end-to-end delay was just slightly higher than the specified minimum but the same was also observed for the non-virtualized base-station. Similar performances was also observed for VB2 and VB3 in the video and web browsing traffic scenarios which proves the effectiveness of spectrum virtualization for different traffic applications.

4.7 Summary

In this Chapter the concept and origin of virtualization was explained in details describing its evolution into the domain of spectrum virtualization. A novel framework for spectrum virtualization for a WiMAX base-station was proposed to enable multiple VNOs share the physical base-station infrastructure particularly the spectrum. The concept of spectrum virtualization was validated using different simulation scenarios that involved validating the slicing of the WiMAX spectrum by the VS-Hypervisor and as well as testing the performance of the virtual base-stations with varying traffic types (video, voice and data) when compared with non-virtualized base-stations.. The results obtained showed the viability of spectrum virtualization as being a reliable means for spectrum sharing. The results also showed that the performance of virtualized base-stations was at par with non-virtualized base-stations in spite of them having lesser spectrum and bandwidth resources.

Chapter 5 WiMAX Network Federation with Virtualization

5.1 Introduction

Spectrum virtualization which has been discussed extensively so far in this thesis, enables the abstraction and sharing of the wireless spectrum resources amongst virtual network operators on a single physical base-station infrastructure. To further expand the advantage of this new concept, the concept of network federation is implemented; which enables multiple physical base-station infrastructures having virtualization capability to create a more spectrally corporative environment, which will enhance the quality of service provided to their end users. This Chapter proposes a novel architecture that enables a physical base-station that already implements spectrum virtualization to be able share its spectrum resources with a corresponding base-station having similar capabilities.

5.2 The Concept of Federation and Virtualization in Networks

The idea of federation has been explored in many networking domains predominantly in the federation of network testbeds [87], [88], [89], data centres [90], personal networks [91], wireless sensors [92], [93], virtualized networks [94] and cloud service federation [95]. Network federation in the domain of virtualization essentially involves the interconnection of two or more domains of the same or different types of virtualization platforms. The federation of virtualized testbeds has been extensively carried out by the Global Environment for Network Innovations (GENI) project which was established in the United States of America (USA), to explore and experiment with networks of the future. The project provides a virtual laboratory for networking and distributed systems for research and education [96]. The GENI project

enables multiple experiment to have access to resources from different testbeds across the USA and even globally [97], [98]. The *Network Federation* concept provides an avenue for combining network resources between similar networking domains to achieve a greater technological and administrative convergence. It provides network providers the advantage of sharing resources across their domain with a far deeper cooperation than SLA contracts.

The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) in its definition of the terminologies of Future Networks (FNs) described *Federation* or Network Federation as a technology that enables the heterogeneous collection of component networks allowing them to operate as a single network even though they are geographically dispersed and managed by different providers. Furthermore, the ITU-T, defined FN as networks able to provide revolutionary services, capabilities and facilities which are difficult to provide using existing network technologies. FN were also described as a federation of new and existing network components [99], [100]. The network federation concept can easily be described using the Figure 5.1 where multiple independent Mobile Network Operators (MNOs) exist in an inter-connected network framework.

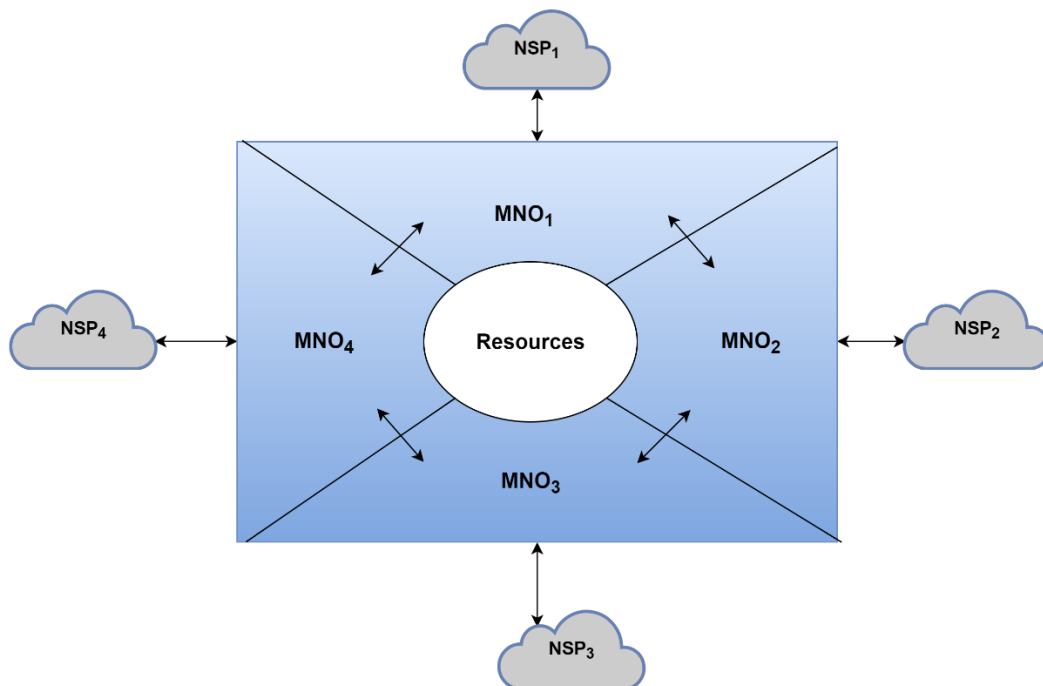


Figure 5.1 Network Federation Illustration.

These MNOs are independently connected to their individual Network Service Providers (NSPs) and the NSPs are dependent of the MNOs for the use their network infrastructure. The purpose of this framework is to enable the sharing of network resources (e.g. spectrum) amongst the MNOs.

5.3 WiMAX Network Federation Architecture

This section describes a novel architecture for WiMAX Network Federation shown in Figure 5.2 for the purpose of sharing spectrum. It enables multiple WiMAX base-stations with virtualization capabilities to be able to interconnect using the spectrum virtualization platform explained in earlier in Chapter 4 with the VS-Hypervisor acting as the core entity in managing this spectrum sharing framework.

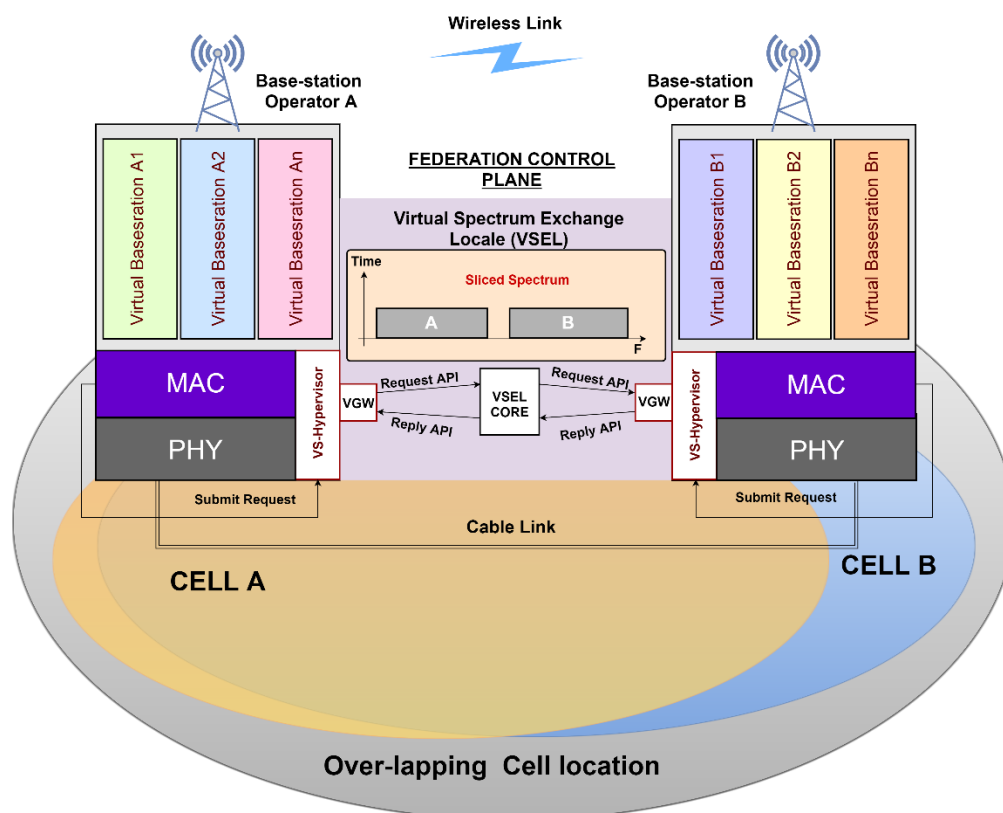


Figure 5.2 WiMAX Network Federation Architecture

The WiMAX base-stations modelled in this architecture are assumed to be operated by different MNOs existing in the same geographical location and having overlapping cells. The base-stations are connected to each other either through cable or wireless links, and it is through these links that virtualization signals between their VS-Hypervisors are exchanged. This architecture is modelled after the SEP architecture discussed earlier in Section 1.2.6. The architecture comprises of a Virtual Spectrum Exchange Locale (VSEL) which forms and represents the federation control plane. At the centre of the VSEL is the VSEL-Core that manages the intercommunication between the VS-Hypervisors of the individual base-stations. Each base-station has a virtual gateway (VGW) that enables the federation control plane (VSEL) to be able to send and receive base-station specific spectrum requests and replies using the federation Application Program Interface (API). The VSEL's features can be described as follows:

- **Infrastructure Neutrality:** The VSEL's request and reply API commands are independent of the virtualization platforms of the base-stations which ensures neutrality because the virtualization platforms may differ and if that is the case, this should not negate the federation process.
- **Single-Interface Federation:** The VSEL provides conceptually a single-interface to destination base-stations regardless of the inter-base-station physical connection.
- **Extensibility of Capabilities:** The VSEL is flexible and adaptable to handle new virtualization functionalities which may be introduced in future enhancements of the system.

5.3.1 Federation Algorithm at the VSEL

The algorithm for federating two base-stations at the VSEL for the purpose of spectrum sharing is illustrated by the flowchart in Figure 5.3. From the algorithm, the VSEL-CORE is originally in an initial state waiting for a base-station to make a spectrum request ($SPECT_{req}$). A requesting base-station (BS_{src}) then makes a spectrum request via a virtual gateway (VGW_{src}) attached to its VS-Hypervisor using federation API commands prompting the VSEL-CORE to leave its initial state. The VSEL-CORE receives this request and queries the destination base-station (BS_{dest}) for the availability of the requested spectrum.

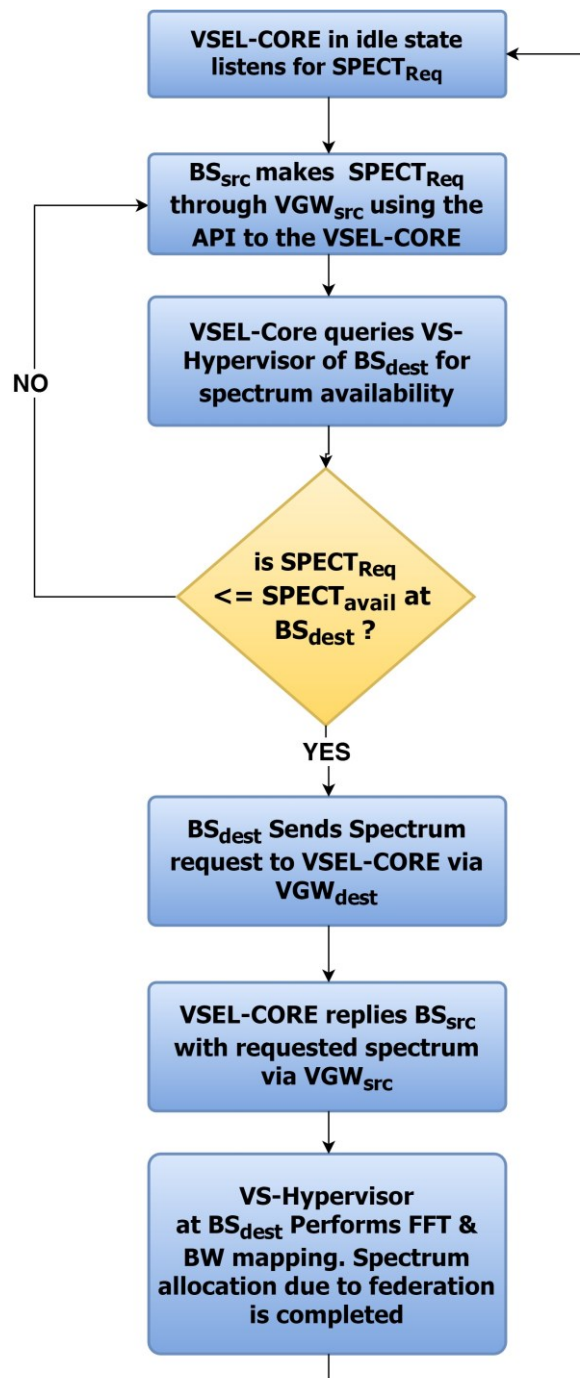


Figure 5.3 WiMAX Federation VSEL Algorithm

If the requested spectrum is available at the destination base-station, the destination base-station replies the VSEL-CORE by sending the requested spectrum via its virtual gateway

(VGW_{dest}) otherwise, the requesting base-station returns to the VSEL-CORE to make a new request. After the VSEL-CORE receives the spectrum allocation from the destination base-station, it then sends a reply using the VSEL API to the requesting base-station. The VS-Hypervisor at the requesting base-station on receiving the allocated spectrum, performs FFT and BW mapping as described earlier in Section 4.4.2.4 of Chapter 4. Upon completion of the FFT and BW mapping, the federation process is accomplished. The implementation of the federation algorithm in OPNET is done using the *wimax_vs_federation* function is shown in Figure 5.4 below:

```

102 static void
103 wimax_vs_federation(int Spect_RQ, int BS_MAC_ID)
104 {
105     /*
106     This function is designed to federate two base-station via their
107     VS-Hypervisors.
108     */
109     /*
110     // Variable Declarations
111     WimaxT_Phy_Profile* local_phy_profile_ptr = OPC_NIL;
112     char profile_name [256];
113     FIN();
114
115     my_objid = my_module_objid;
116     op_ima_obj_attr_get_str (my_module_objid, "PHY Profile", 256, profile_name);
117     local_phy_profile_ptr = (WimaxT_Phy_Profile*) oms_data_def_entry_access ("wimax PHY Profiles", profile_name);
118
119     if(Spect_RQ <= BS_SPECT_2)
120     {
121         if(BS_MAC_ID == 1)
122         {
123             //Pass accepted spectrum request for FFT and BW mapping
124             wimax_vs_bw_estimation_calc(Spect_RQ);
125
126             //PHY Setting for requesting base-station in the case (base-station 1) is re-configured
127             local_phy_profile_ptr->num_subcarriers = BS_Subcarriers_1;
128             local_phy_profile_ptr->bandwidth = BS_BW_1;
129         }
130     }
131     FOUT;
132 }
133
134
135
136
137
138
139
140
141

```

Figure 5.4 WiMAX Network Federation Function in OPNET

5.4 Network Federation Requirements

To fully realize the concept of network federation, certain requirements need to be fulfilled. The scope of this thesis does not cover these requirements in terms of implementation, it is anticipated that as the WiMAX network federation concept expands into real-life execution, these requirements will have to be established.

- **Membership Management:** The WiMAX network federation is a cooperation of different base-stations. The number of base-stations attached to this federation needs to be properly managed and mechanisms must be defined for the initialization of new base-stations into the federation as well as the configuration and storage of membership information [6].
- **Self-Organization:** The federation should be self-organized which will require the development of policies and rules that determines when the formation of a federation between base-stations will take place. These policies will need to be automated using the Self Organization Network (SON) concepts [101] which will help in reducing the OPEX the federated network.
- **Security:** Security is an important issue to consider in the WiMAX network federation. Federated base-stations need to have their membership verified at every instance a spectrum request is made and a secured transport channel within the VSEL needs to be established to secure the request/reply API spectrum exchange. This is in similar fashion to the SEP framework [6].

5.5 Implementation of Network Federation

In this section, the implementation of the network federation for WiMAX is discussed. The implementation was carried out using the OPNET Modeler wherein the VS-Hypervisors residing in each physical base-station are able to communicate based on the federation algorithm previously described. The inter-VS-Hypervisor communication in this case was carried out using memory-based information interchange but it is assumed that in a real-life scenario, IP packets will act as the delivery mechanism within the communication link

(wired/wireless) connecting the federated base-stations. An Illustration of the simulation setup is described in Figure 5.5.

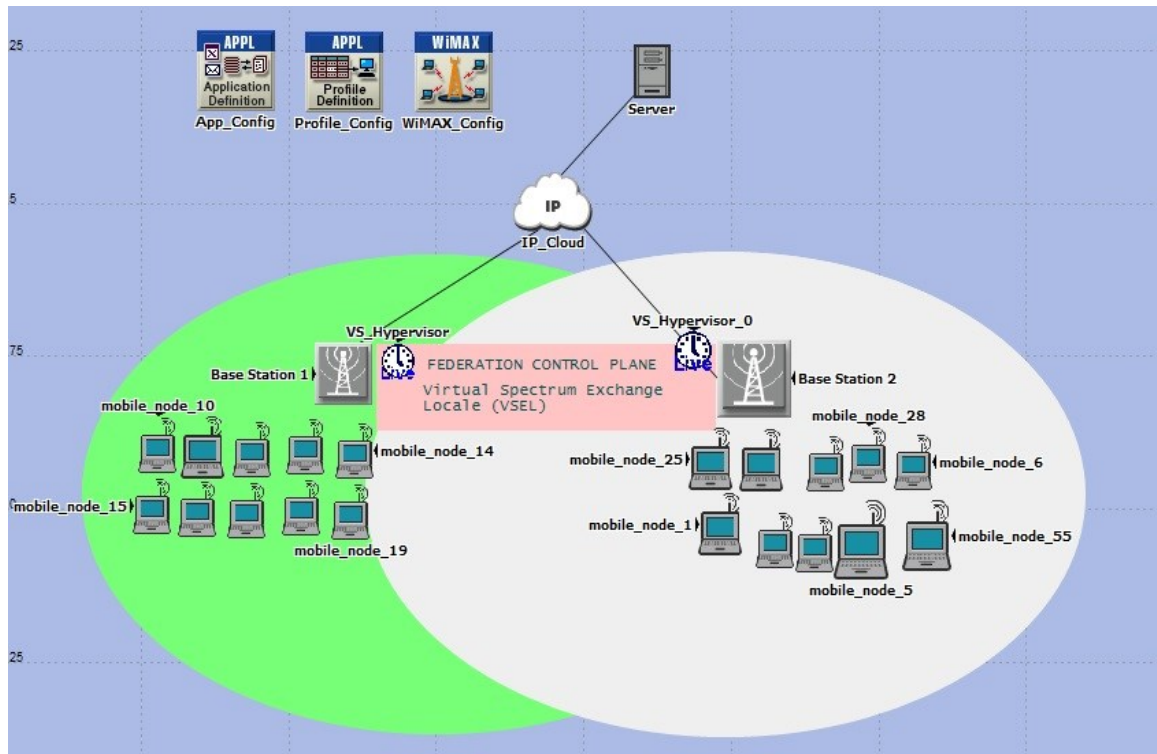


Figure 5.5 WiMAX Federation Simulation Setup in OPNET

5.5.1 Simulation Scenario

The essence of WiMAX network federation in the context of this thesis is to enable the sharing of spectrum which ultimately will increase the throughput as well as the data-rate for the base-station needing additional spectrum and bandwidth. The main advantage of this technology in terms of spectrum sharing is that it provides an alternative for a base-station needing more bandwidth to be able to meet the QoS parameters for the services it provides to its subscribers. Especially when it receives traffic beyond its normal capacity. To substantiate the efficacy of the federation concept, the simulation scenario carried in this research comprises of two physical base-station with spectrum virtualization capabilities using the VS-Hypervisor. Base-station 1 (BS1) depends on base-station 2 (BS2) for extra spectrum/bandwidth. To trigger the process of federation in the simulation, a spectrum request is sent from BS1 to BS2 at a specific

time. BS1 is configured to have more subscribers (therefore more traffic demand) than BS2. Details of the simulation parameters are shown in the Table 5.1.

It is important to note that in this scenario, simulations were not ran for voice and data because compared to video (HD video streaming, as is the case in this scenario), their bandwidth demand and throughput are far lesser than that of video which is evident when the throughput results for voice, data and video are compared from chapter 4–section 4.5.2.2, 4.5.2.3 & 4.5.2.4. Therefore it is assumed that if the network federation concept performs well with video traffic, it will by extension perform proportionally well with voice and data traffic.

Table 5.1 Simulation Parameters for WiMAX Network Federation using Video Traffic.

Parameters	Configuration
Number of Base-stations with spectrum virtualization capability	Two (2)
Circular Cell Radius	5Km
Number of FFT & Subcarriers (Spectrum) per Base-station	BS1: 512 BS2: 2048
Amount of Bandwidth per Base-station	BS1: 5 MHz BS2: 20MHz
Frequency Band	5GHz
Duplexing Technique	TDD
Permutation Scheme	PUSC
Number of Subscriber Stations per Base-station	BS1: 50 BS2: 10
Traffic Configuration	- Video Streaming with high resolution with a frame interarrival time of 15 frames/sec. - IP Telephony (VoIP) - Web Browsing (Data)
Seed	128
Simulation Kernel	Optimized
Simulation run time	15mins (900secs)

5.6 Results and Analysis

This section discusses and analyses the results gotten after conducting simulations based on the parameters shown in Table 5.1. The simulation was initially carried out without triggering the process of federation and the essence was to recognize the usage of spectrum for the two

base-stations and also to assess their throughput without federation. Video traffic was initially configured for the two base-stations in the case where there was no federation and in the case where there was federation. Thereafter, voice and data (web browsing) traffic was also configured for both base-stations and simulations were conducted separately. The network is first of all analysed for video traffic (video streaming) since it demands more bandwidth/spectrum allocation from the base-stations. The video, voice and data traffic configuration in OPNET for this simulation is similar to the set-up in Section 4.5.2.3. Figure 5.6 shows the initial spectrum available to BS1 and BS2 before the federation process and Figure 5.7 shows the throughput for the video streaming application traffic sent on both base-stations. It can be seen that the throughput for BS2 far exceeds that of BS1 because BS2 has a higher spectrum (2048 subcarriers) than BS1 (512 subcarriers) and lesser number of subscribers. To improve the throughput of BS1, the federation process was triggered in a subsequent simulation at a selected time interval.

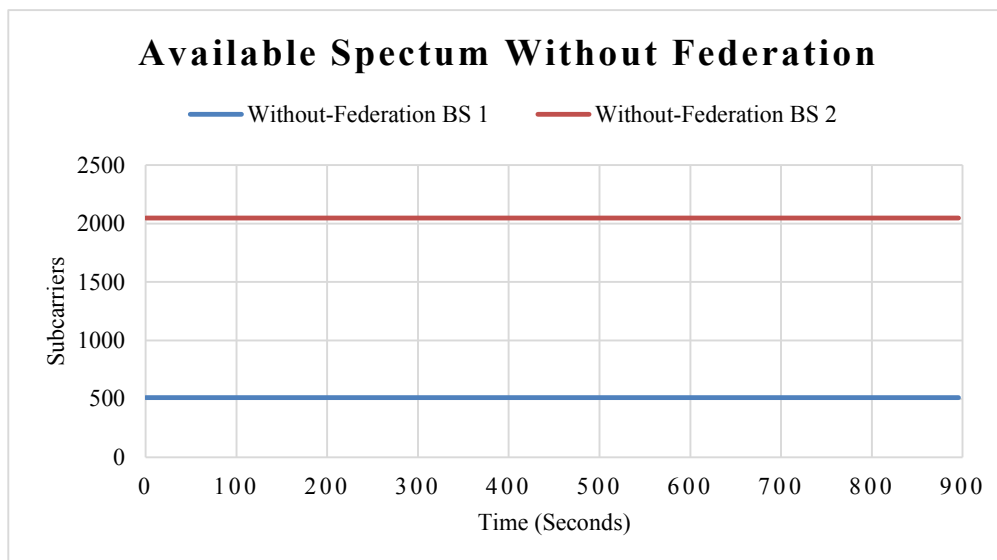


Figure 5.6 Available Spectrum for BS 1 & 2 Without Federation

The federation process was initiated at simulation time 240 seconds with BS1 requesting a spectrum size of 512 subcarriers from BS2. The changes in spectrum on both BS1 and BS2 is shown in Figure 5.8. It can be seen that after federation, BS1 got an increase in subcarriers (Spectrum) from 512 to 1024 and BS2 got a reduction of subcarriers from 2048 to 1024.

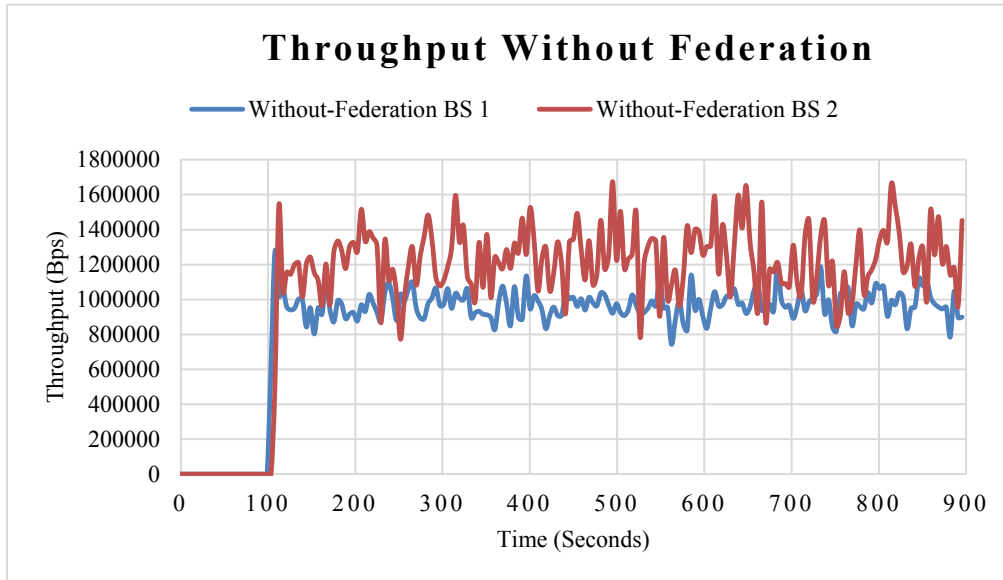


Figure 5.7 Throughput for BS 1 & 2 Without Federation for Video Traffic

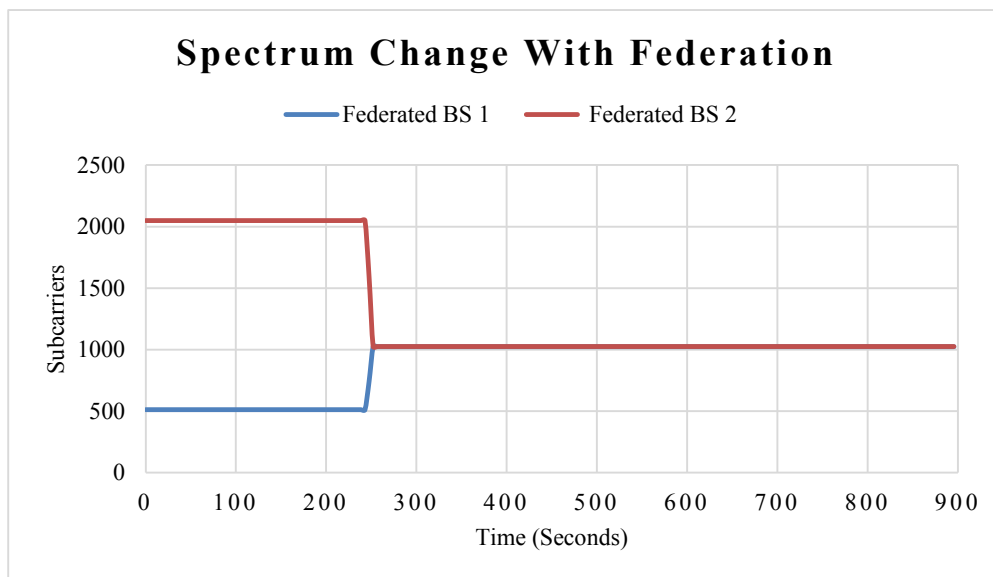


Figure 5.8 Spectrum Changes in BS1 & BS2 with Federation

The throughput result with federation illustrated in Figure 5.9 show the significant improvement in the throughput of BS1 with little changes occurring with throughput of BS2. A merger of the throughput results of BS1 before and after federation is shown in Figure 5.10 and it highlights the leap in throughput for BS1 after federation. This is as a result of an increase in

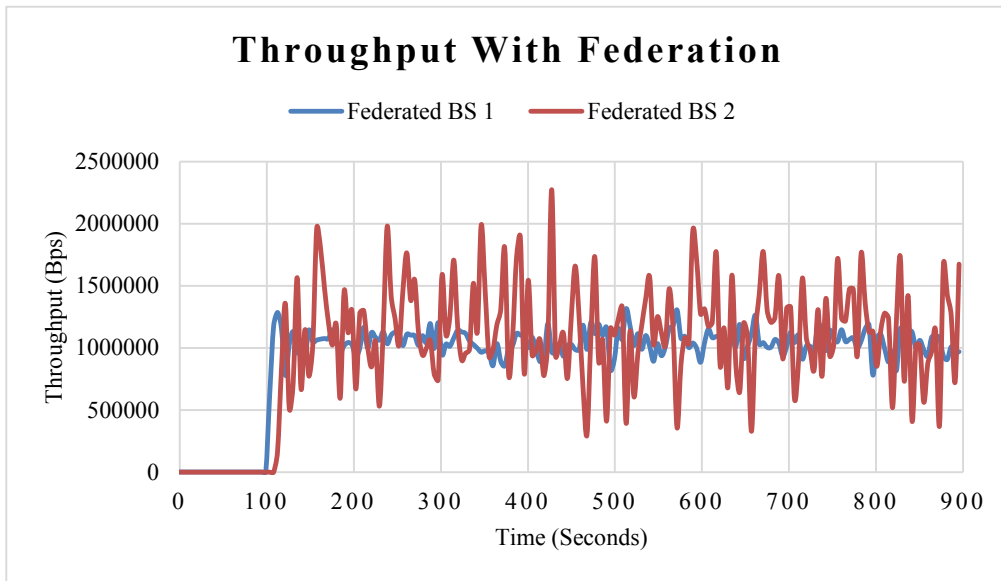


Figure 5.9 Throughput of BS1 & BS2 With Federation for Video Traffic

the number of bandwidth channels for BS1 which made is possible for it to increase its allocation to its subscribers.

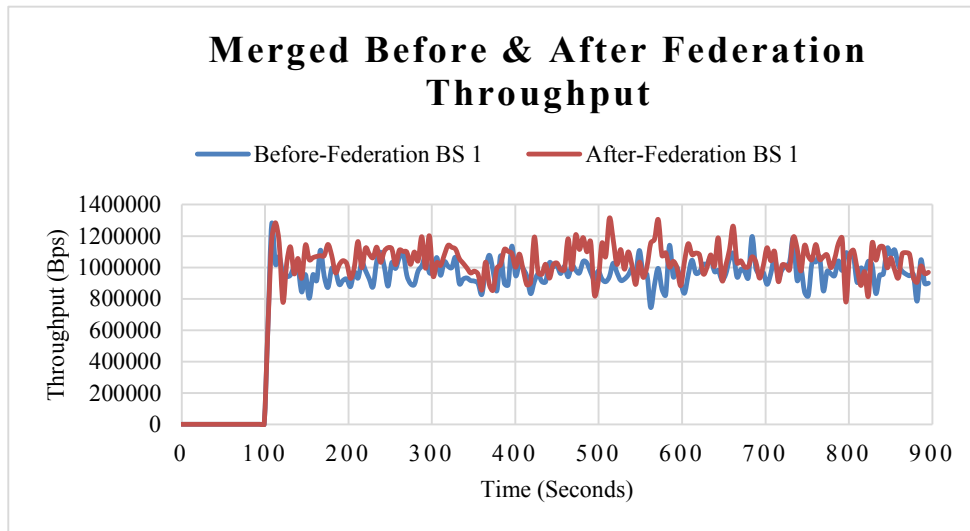


Figure 5.10 BS1 Before and After Federation Throughput for Video Traffic

An average of the throughput for BS1 before and after federation is expressed in the Figure 5.11 below:

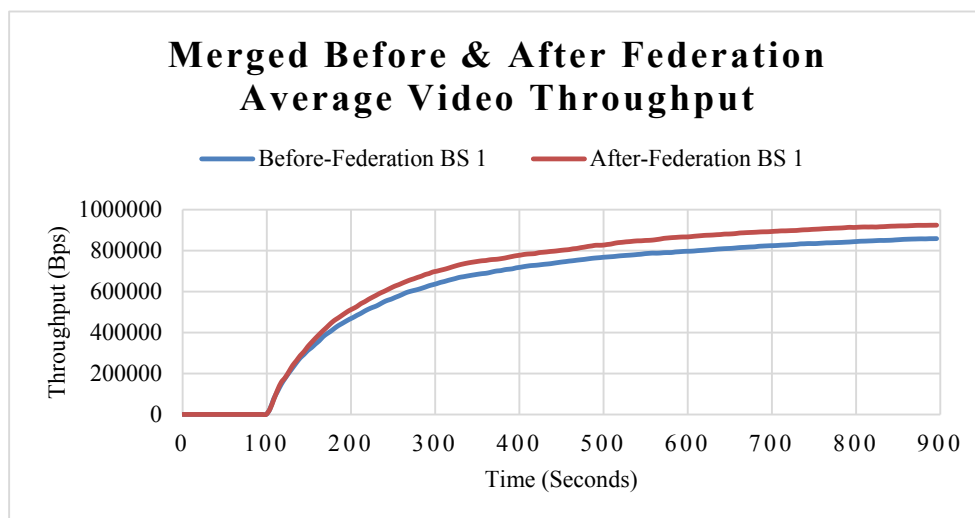


Figure 5.11 BS1 Before and After Federation Average Throughput for Video Traffic

As regards the average delay performance of the federation system for BS1, the Figure 5.12 shows that the delay drastically reduces after federation due to the fact that the base-station that had more spectrum allocation as well as more bandwidth channels to allocate to its subscribers and the subscribers had a lesser waiting time for bandwidth allocation in the downlink direction.

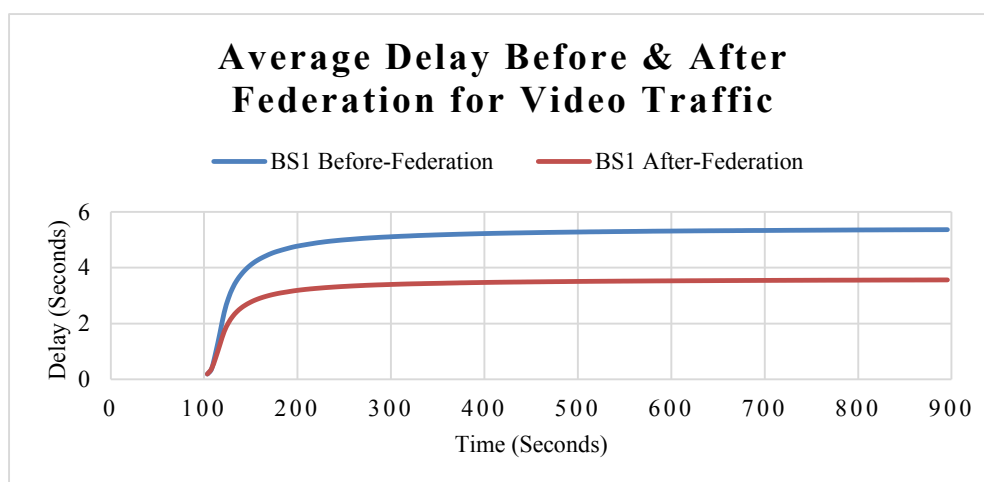


Figure 5.12 BS1 Before and After Federation Average Delay for Video Traffic

It is also important to consider the effect of federation on BS2 which is the spectrum donor in this scenario. Figure 5.13 shows the change in throughput for BS2 after federation and it can be observed that there is a slight decline in its throughput which does not necessarily affect its ability in meeting the QoS service requirements for its subscribers.

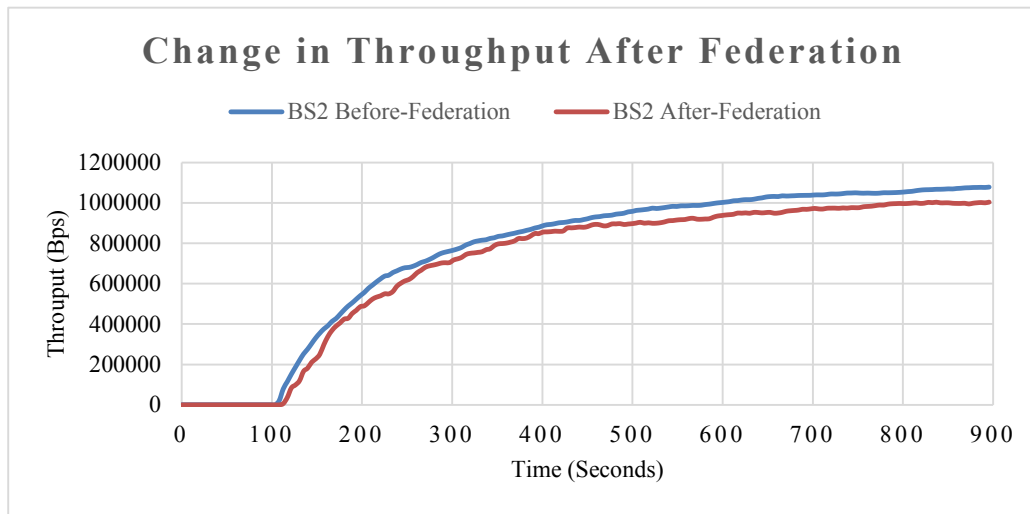


Figure 5.13 Throughput Change in BS2 After Federation for Video Traffic

To provide a more comprehensive view of the performance of the network federation concept in relation to other traffic types, it is important to also analyse the performance of VB1 when configured with voice and data traffic respectively. The Figure 5.14 shows the voice traffic average throughput for BS1 before network federation was initiated and after its initiation.

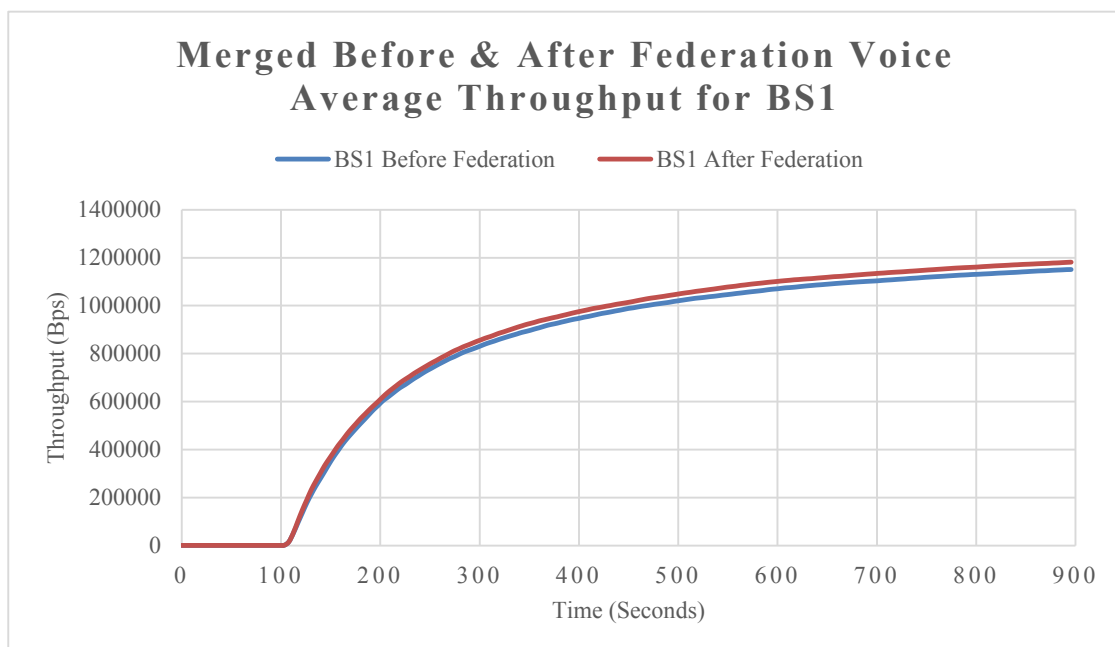


Figure 5.14 BS1 Before and After Federation Average Throughput for Voice Traffic

The result shows a marginal increase in throughput for VB1 which is due to the fact that the mobile WiMAX standard defines a minimum reserved data rate for VoIP traffic (see Table 2.4)

which was satisfied by VB1's initial spectrum allocation (512 subcarriers); but its increased spectrum allocation could not cater for the maximum WiMAX standard specification for voice traffic QoS data-rate (which requires a spectrum allocation of 2048 subcarriers at 20MHz bandwidth). Hence a significant increase in its spectrum allocation was not fully achieved.

In spite of the marginal increase in the voice throughput for BS1, Figure 5.15 shows a significant reduction in traffic delay for voice in VB1. This is due to the extra frequency channels available to BS1 as a result of spectrum sharing via network federation.

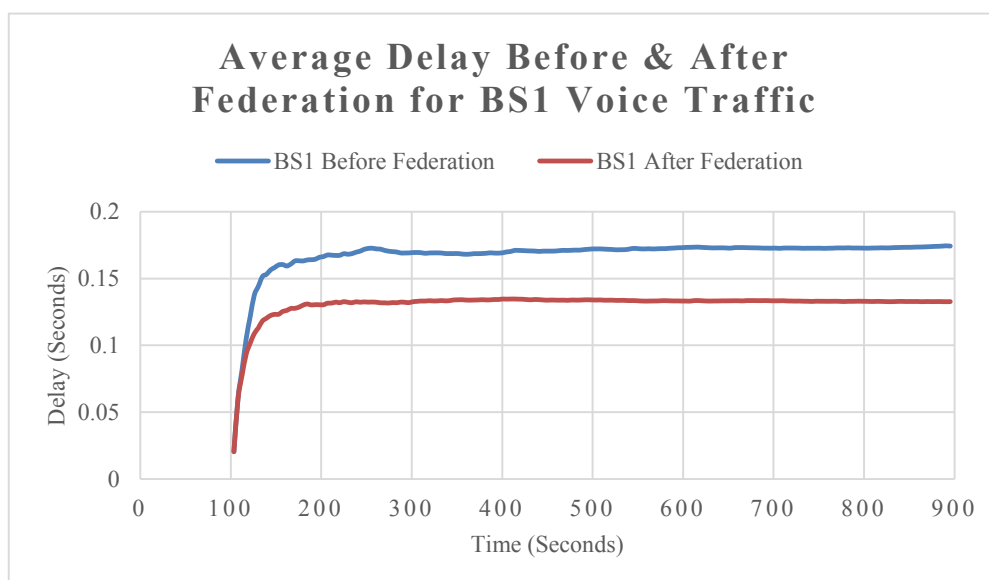


Figure 5.15 BS1 Before and After Federation Average Delay for Voice Traffic

Considering the performance of BS1 in relation to data traffic, Figure 5.16 illustrates the before and after average throughput of BS1 for web browsing traffic; showing a very significant increase in throughput for VB1. This is due to the fact that mobile WiMAX defines a maximum traffic data-rate for data traffic based on its QoS parameters. Since VB1 received an increase in its spectrum allocation due to network federation, more frequency channels were available to for it to allocate to its subscribers. Its increased spectrum allocation resulted in an increase in its data-rate leading to its very high throughput after the federation process.

VB1 also experienced a significant drop in data traffic delay after the federation process as shown in Figure 5.17. This contributed obviously to its increased data throughput; reason being

that more frequency channels were allocated by VB1 to its subscribers for data transfer, both in the uplink and downlink direction.

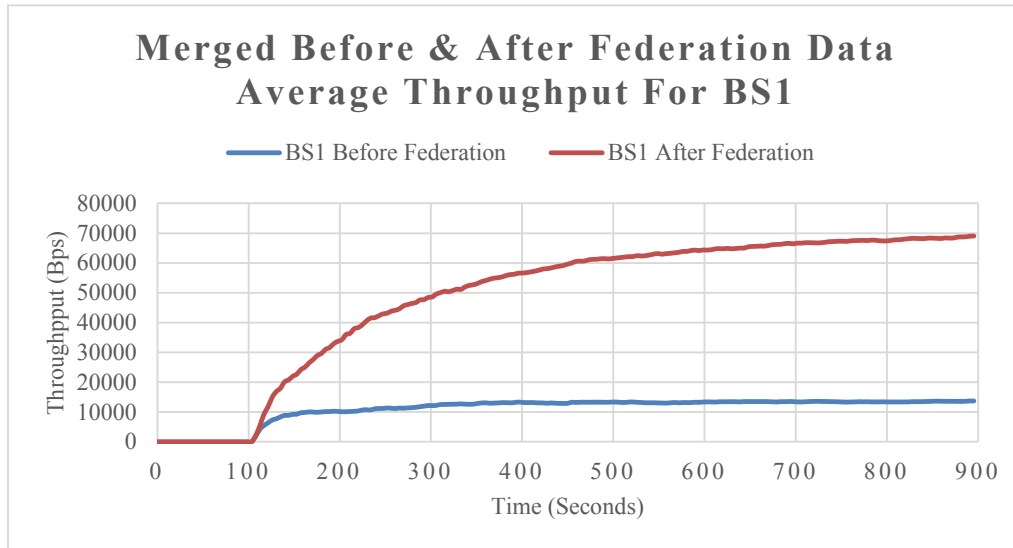


Figure 5.16 BS1 Before and After Federation Average Throughput for Data Traffic

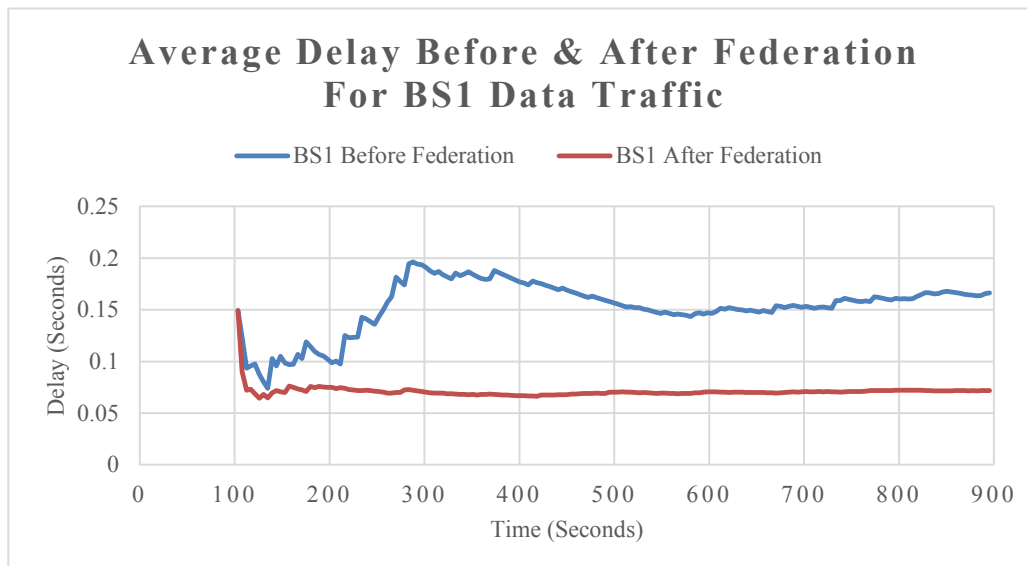


Figure 5.17 BS1 Before and After Federation Average Delay for Data Traffic

5.7 A Novel Testbed for the Implementation of WiMAX Spectrum Virtualization and Network Federation

This section describes the parameters of the software testbed for WiMAX spectrum virtualization and network federation that can be changed and manipulated by future researchers who would want to carry-on from where this research left off. It also discusses briefly the areas of application the testbed can expanded to. The major parameters that can be manipulated are listed below:

- The VS-Hypervisor's Process Models for spectrum virtualization and network federation described in sections 3.5.23.5.2.1 and 3.5.2.3.
- The FFT size indexes described in **Appendix C**. The indexes can be increased to match higher bandwidth and subcarrier sizes but changes will also be required in OPNET's WiMAX PHY support header and extension files as a result of this action.
- Changes can be made to the SLA types in the *wimax_vs_bw_estimation_calc()* function which resides in the *wimax_vs_est (.h/.ex.c)* described in section 3.4.
- More base-stations can be added to federation simulation set-up in section 5.5 with each base-station being paired with its own VS-Hypervisor. The VS-Hypervisor's federation process model will need to be remodelled to accommodate the federation of more than two base-stations.

Generally to further expand the use of the spectrum virtualization and network federation software testbed described in this thesis, 3.4 changes will need to be made to their respective process models in the VS-Hypervisor as well as designing newer process models to fit-in with the PHY and MAC layers of the wireless technologies were their application will be effected.

5.8 Conclusion

The results gathered in the simulation done for network federation which was performed specifically for the purpose of spectrum sharing; provides evidence that the network federation concept offers an innovative solution to efficient resource sharing in a wireless network. BS1 which was the base-station needing additional spectrum experienced a significant increases in its throughput for the video streaming traffic sent on its network after federation was triggered at point during the simulation process. Its average delay for the video, voice and data traffic applications reduced exponentially, since it had more frequency channels to allocate to its subscribers therefore lesser waiting time for bandwidth allocation in the downlink direction by BS1. The federation process did not have an adverse effect of the throughput for BS2 which was the base-station that permitted the sharing of a portion of its spectrum.

This research has shown that network federation for spectrum sharing serves as an economical solution for network providers that want to provide additional bandwidth channels to their subscribers. For instance, operators wanting to provide intensive multimedia applications services e.g. videoconferencing, High Definition (HD) video streaming and VoIP besides not being able to afford additional spectrum/bandwidth to meet this demand, can achieve their desired throughput through network federation. It offers a cooperative environment for network providers to be able to tap into the under-utilized spectral resources available on similar network platform especially when their network coverage overlaps. The ideas that have been discussed in this thesis are not specific only to WiMAX networks but can be duplicated in other 4G networks such as LTE and the ideas can also be applied and improved upon for the fifth generation networks (5G).

5.9 Summary

In this Chapter, the research focus was to develop a network federation platform for a WiMAX network that enables the sharing of spectrum. The network federation concept was built on the spectrum virtualization platform already discussed in Chapter 5 with the VS-Hypervisor acting as the main virtualization entity. A novel architecture for WiMAX network federation for the purpose of spectrum sharing was explained and discussed with the introduction of a novel federation control plane referred to as the Virtual Spectrum Exchange Locale (VSEL). The foreseen requirements for the efficient implementation was critically outlined. A novel algorithm for the implementation of network federation in the VSEL was also described. Simulations were ran and structured based on the proposed architecture for network federation and the results obtained proved the efficacy of the federation concept which will improve the way spectrum resources are utilized in a wireless network.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

In conclusion, it is important to reiterate the key goals of this research. This research set-off to meet three main objectives:

- Design and implement a novel architecture for WiMAX spectrum virtualization.
- Design and also implement a novel architecture for federating WiMAX base-stations using a virtualization platform.
- And the last objective was to develop a software testbed using the OPNET Modeler to model the new network architectures for WiMAX spectrum virtualization and network federation.

In this thesis, WiMAX Spectrum virtualization was implemented in accordance with the OFDMA PHY layer arrangement as stipulated by the mobile WiMAX IEEE 802.16e standard. The spectrum was sliced and virtualized using a scheduling algorithm by applying a set of SLA contracts (FA, DA and BEA). The scheduling algorithm was managed by a novel virtualization entity called the VS-Hypervisor. The VS-Hypervisor being the main virtualization entity, slices the WiMAX spectrum based the mobile WiMAX S-OFDMA subcarrier/FFT sizes ranging from (128 – 2048) along with their corresponding bandwidth sizes which ranges form (1.25 – 20MHz).

The results obtained from implementation WiMAX spectrum virtualization, proved and validated of the proposed architecture as being able to virtualize the WiMAX spectrum. The results also showed that the performance (in terms of throughput and end-to-end delay) of virtual base-stations that share a limited spectrum size with respect to data, voice and video traffic was relatively at par with a physical base-station having the entire spectrum size shared

by the virtual base-stations. With WiMAX spectrum virtualization using the proposed approach in this thesis, it will help to encourage the entrance of new WiMAX operators and greatly reduce the CAPEX and OPEX especially for operators wanting to deploy their services in rural and emerging markets.

As regards WiMAX Network federation, this research proposed a novel architecture for federating multiple WiMAX base-stations whose cellular coverage areas overlapped. The federation was based on their virtualization platforms that enabled their interaction and negotiation for spectrum between the base-stations. In the WiMAX federation architecture, a control plane environment known as the Virtual Spectrum Exchange Point (VSEL) is described and it is at this point that spectrum negotiations are made via the VS-Hypervisors of the interacting base-stations. The results obtained for WiMAX Network federation showed that a base-station can increase its throughput by requesting for additional spectrum from a base-station that has more than enough and is willing to share. This proposed architecture is generic only to a WiMAX network but can be deployed in other wireless broadband technologies like LTE and maybe possibly adopted in the development of 5G networks.

It is hoped that the software testbed for both WiMAX spectrum virtualization and network developed in the research can be used as a research tool by university undergraduates in understanding the concepts of spectrum virtualization and network federation. Masters students can use it as a starting platform for expanding the ideas already expressed in this research.

6.1.1 Research Discussion and Limitations

This research work undertook the task of proffering solutions to the prevailing problem of spectrum management particularly for wireless broadband networks using WiMAX as a case study. The methodologies adopted in solving this problem which were spectrum virtualization and network federation, was based on the approach of spectrum sharing. Comparing the results gotten from the performance analysis of WiMAX spectrum virtualization (Section 4.5) in relation to the concept of virtualization in section 4.1, a VMM i.e. a hypervisor or the VS-Hypervisor, which is the VMM entity of interest in this thesis, must satisfy three important properties. These properties are: fidelity, Isolation and Performance.

As regards *fidelity*, which mandates the VMM to create an environment for the VM which is identical to the original hardware resource, it is clear from Figure 4.23 and Figure 4.25 that the wireless spectrum was adequately shared by the VS-Hypervisor and the spectrum was utilized by the all the VBs just as a physical base-station would have done. In terms of *isolation*, it can be seen also from Figure 4.23 that the each of the individual VBs had a distinct slice of the spectrum with no overlaps and interference. Hence the VS-Hypervisor could be judged to have satisfied this criteria. Finally, regarding *performance*, the results from the traffic based analysis in section 4.5.2 showed clearly that the VBs performances were at par with the non-virtualized base-stations for all three traffic categories (voice, video & data). This is a testament to the effectiveness of the VS-Hypervisor in slicing and allocating the radio spectrum to meet the SLA requirements for all the VBs. It is also important to note that the spectrum virtualization results gotten from this research, shows close similarities with the results derived from the LTE spectrum virtualization research [1], [13]; with regards to the hypervisor's performance and the general performance of the VBs to various network traffic.

One limitation of the WiMAX spectrum virtualization approach carried out in this research is that three SLA contracts were defined and experimented for three VBs; whereby each SLA contract was assigned per VB. Assuming there was a situation where there were two or more VBs having the same SLA contract, for instance DA, which requires estimating the number of OFDMA subcarriers for spectrum allocation; there should be a mechanism included in the operation of the VS-Hypervisor to determine who gets first priority in terms of spectrum allocation. This at the moment does not exist in the operation of the VS-Hypervisor. Another limitation arises if there are multiple cases of all three contracts with all the VBs wanting allocation from a fixed spectrum size. This may result in an uneven distribution of the spectrum, therefore there is a need for a mechanism that ensures fairness in the allocation of spectrum as well as places VBs in a queue if there is no spectrum available for allocation. This situation was not addressed in this research, hence acts as a major limitation in terms of overall efficiency, intelligence and sophistication of the VS-Hypervisor.

Paying more attention to the network federation implementation carried-out in this research for WiMAX, it is very clear from all the results gathered, that the federated member base-stations, particularly the spectrum resource requesters and receivers experienced considerable increase

in throughput as well as a significant reduction in delay in their network performance. In terms of quantification, a throughput increase of 8.75% and a 36.36% reduction in delay was obtained from the simulation results using the OPNET Modeler statistical tools. This in itself is a momentous breakthrough in the validation of network federation via virtualization as a concept because subsequent works [6], [10], [94] dwelt more on architectural concepts and policy designs.

However, the only obvious limitation of the network federation concept discussed in this thesis is that the experimentation was done for only two federated base-stations. As a result of this, it is difficult to evaluate a situation where there are more than two base-stations connected in a federation; whereby a member base-station can request spectrum from more than one base-station simultaneously and the impact that would have in its overall throughput and delay performances.

6.2 Theoretical Contributions and Implications

This section discusses the major theoretical contributions of this thesis and their implications for future research works.

One of the major theoretical contribution of this thesis is the dynamic and creative approach adopted in utilizing the WiMAX's S-OFDMA parameters for spectrum slicing and sharing. This approach to WiMAX spectrum slicing stays within the confines of the IEEE 802.16e standard and by implication makes it easy for incorporation into the standard, most especially for its real-life application and implementation.

Another theoretical contribution is the expansion of the idea of wireless virtualization through the design of a novel WiMAX spectrum virtualization architecture. This will by extension open new research doors to the management of the radio spectrum both for current 4G technologies but also for future networks.

Lastly, another major theoretical contribution of this research is the adoption and modification of current network federation frameworks for the federation of virtualized networks tailored

specifically for spectrum sharing. This again pioneers a new research paradigm for radio spectrum management.

6.3 Future Work

This section describes the major anticipated areas where this research could be expanded to in the near future.

- **Hardware Implementation of Software Testbed:** All the implementations carried out in this research was purely software based. It will be interesting to see the proposed research ideas of this thesis being implemented on a hardware test-bed or platform.
- **Improved VS-Hypervisor Intelligence:** The addition of more intelligent features to the VS-Hypervisor such as the ability to be able to detect when a virtual base-station is idle (i.e. not transmitting or receiving) and being able to apportion the spectrum of an idle virtual base-station to another virtual base-station who may be needing more spectrum, without going against the already set SLA contracts.
- **Network Federation Expansion Implementation:** The implementation of WiMAX network federation was limited to only two base-stations. Further investigation can be made to test the proposed architecture for federation with more base-stations.
- **Grid Federated Networks:** The cooperation of federated wireless broadband networks can also be researched and investigated similar to the concept of Grid-federation of computer network clusters [101], [102], [103].

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Appendix A : Global Repository Access Code in OPNET

This code shows the function that carries out spectrum allocation for the virtual base-stations by re-allocating the spectrum available on the physical base-station. It also shows the portion of code by which the VS-Hypervisor has access to the OPNET Global Repository where the WiMAX PHY settings can be re-configured.

```
static void
wimax_bs_control_spectrum_reallocation(void)
{
    /*This is a hooking function that interacts with the VS-Hypervisor and enables
    there-allocation of spectrum and bandwidth to the MAC of the individual BS and
    SS
    */
    /*Because this function is to reallocate spectrum, the only way to do that is
    to have access in the global data repository of WiMAX PHY and make the necessary
    changes.
    */
    /*This was done to re-configure the PHY parameters of three virtual base-
    stations */
    /*Decalring variables that provide links to the repository*/

    WimaxT_Phy_Profile*    local_phy_profile_ptr = OPC_NIL;
    char                   profile_name [256];
    double                 alloc_bw;

    FIN(wimax_bs_control_spectrum_reallocation());

    BASE_Station_MAC = my_mac_address;
    my_objid = my_module_objid;
    op_ima_obj_attr_get_str (my_module_objid, "PHY Profile", 256, profile_name);
    local_phy_profile_ptr = (WimaxT_Phy_Profile*) oms_data_def_entry_access
    ("Wimax PHY Profiles", profile_name);
}
if(my_mac_address == 1)
{
    local_phy_profile_ptr->num_subcarriers = BS_Subcarriers_1;
    local_phy_profile_ptr->bandwidth = BS_BW_1;
    Sthandl_BS_Subcarriers_1 = local_phy_profile_ptr->num_subcarriers;
    alloc_bw = local_phy_profile_ptr->bandwidth;
    bw_stathandl_1 = alloc_bw;
}
```

**Global
Repository
access.**

```
    }
    if(my_mac_address == 2)
    {
        local_phy_profile_ptr->num_subcarriers = BS_Subcarriers_2;
        local_phy_profile_ptr->bandwidth = BS_BW_2;
        Sthandl_BS_Subcarriers_2 = local_phy_profile_ptr->num_subcarriers;
        alloc_bw = (local_phy_profile_ptr->bandwidth * 1000000.0);
        bw_stathandl_2 = alloc_bw;
    }
    else if(my_mac_address == 3)
    {
        local_phy_profile_ptr->num_subcarriers = BS_Subcarriers_3;
        local_phy_profile_ptr->bandwidth = BS_BW_3;
        Sthandl_BS_Subcarriers_3 = local_phy_profile_ptr->num_subcarriers;
        alloc_bw = local_phy_profile_ptr->bandwidth * 1000000.0;
        bw_stathandl_3 = alloc_bw;
    }
    else
    {
        FOUT;
    }
}
```

Appendix B : OPNET WiMAX PHY Data Structure

Code

This code shows the OPNET WiMAX data structure for the WiMAX OFDMA PHY profile. The variables in this data structure hold the WiMAX PHY values particularly spectrum values.

```
struct WimaxT_Phy_Profile
{
    char*          name;
    WimaxT_Phy_Type type;
    double         frame_duration; /* in seconds */
    double         symbol_duration; /* in seconds */
    double         ul_duration; /* in seconds, excluding RTG */
    double         dl_duration; /* in seconds, including preambles, excluding
RTG */
    int            num_symbol_times_per_frame;
    int            num_symbols_per_frame;

    /* Begin Frame Structure */
    int            duration_FCH; /* in symbols, used only in SC*/
    int            duration_preambles; /* in symbols */
    double         duration_TTG; /* in seconds */
    double         duration_RTG; /* in seconds */
    int            dl_map_rep_count;

    /* Fast Feedback area definition */
    int fast_feedback_symbols;
    int fast_feedback_subch;
    int fast_feedback_slots;

    /* The contention areas occur in the UL subframe. */
    /* In OFDMA, these contention areas are rectangular, */
    /* aligned to the left edge of the UL subframe. Thus, */
    /* each area is specified by two dimensions: # symbol */
    /* times, # of subchannels. The first area (initial and */
    /* handover ranging) starts at the top left corner of */
    /* the UL subframe. Each subsequent area follows below */
    /* the previous one, on the frequency axis. */
    /* Number of symbol times used for contention. Used for */
    /* both Single Carrier (SC) and OFDMA. The name of the */
    /* data member reflects OFDMA use cases, out of which */
    /* SC use case is just a subset. */
    int contention_irng_ho_symbols; /* for OFDMA: I.Rng,HO; for SC: I.Rng. */
    int contention_prng_bwr_symbols; /*for OFDMA: P.Rng./Bw Req; for SC:
Bw Req. */

    /* Number of subchannels used for contention. */
    /* Used for OFDMA only. */

```

```

int                contention_irng_ho_subch;
int                contention_prng_bwr_subch;

/* Based on the dimensions in (symbol times, subchannels) */
/* defined for each contention area, we can count how many */
/* transmission opportunities (slots) can be accommodated */
/* within the contention area in each frame. The number of */
/* slots per frame is useful in counting backoff. Deriving */
/* the number of slots per frame in each category is based */
/* on the constant size of a slot in units of: */
/* subchannel x symbol time for OFDMA (for SC, symbol time).*/
int                contention_irng_ho_slots;
int                contention_prng_bwr_slots;

/* This is used only in Single Carrier, because */
/* the allocation quantum is defined on each zone */
/* arising from frequency division, in OFDMA. */
int                allocation_quantum; /* allocation quantum, in symbols */
/* allocation quantum, in subchannels is always 1 */

Boolean           is_uldl_boundary_variable;
int               num_symbol_times_per_ul; /* relevant only for fixed ul/dl */
int               num_symbol_times_per_dl; /* relevant only for fixed ul/dl */
/* End Frame Structure */

WimaxT_Duplexing_Technique duplex_mode;
double            tc_overhead_factor; /* proportion of FEC block */

/* Begin Frequency Band */
double            base_frequency; /* GHz */
double            bandwidth; /* MHz */
int               num_subcarriers;
int               fft_index;
/* End Frequency Band */

/* OFDMA-specific parameters, related */
/* to frequency division. */
/* These pointers stay NIL for SC. */
WimaxT_Frequency_Division* dl_freq_division_ptr;
WimaxT_Frequency_Division* ul_freq_division_ptr;
};

```

} *Portion of code where
spectrum is
reconfigured*

Appendix C : FFT Size Index Function in OPNET

The appendix shows the OPNET code that sets-up the FFT index for WiMAX.

```
int
wimax_phy_support_fft_size_index_get (int num_subcarriers)
{
    int fft_index = N2048;

    /** Converts an FFT size into a predefined index.    **/
    FIN (wimax_phy_support_fft_size_index_get ());

    /* The FFT size is the number of subcarriers.    */
    switch (num_subcarriers)
    {
        case 2048:
            fft_index = N2048;
            break;
        case 1024:
            fft_index = N1024;
            break;
        case 512:
            fft_index = N512;
            break;
        case 128:
            fft_index = N128;
            break;
        default:
            /* Not a known FFT, return 1024    */
            fft_index = N1024;
            break;
    }

    FRET (fft_index);
}
```