Hybrid Wireless Broadband Networks

Juwita Mohd Sultan

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Abstract

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A hybrid system is an integration of two or more different systems, particularly in this thesis referring to wireless broadband networks. However, to provide end-to-end quality of service (QoS) in a hybrid system is a challenging task due to different protocol in each system.

In this thesis, we aim to improve the overall performance of hybrid networks in a disaster management by addressing the challenges as well as the problems in a homogeneous network. Such an approach allows more efficient multi-parameter optimization and significant improvements in the overall system performance. More specifically, we introduce two novel algorithms. The first is the novel end-to-end QoS algorithm for hybrid wireless broadband networks. We proposed the end-to-end QoS maps based on particular chosen parameters and analyse the simulation results. The QoS maps are applied to a few scenarios, and the performance evaluation of the constructed network is presented. Based on the results obtained by software simulation tools, the performance validation shows that the hybrid network has specific advantages and constraints in terms of number of users, preference, coverage and applications.

The second algorithm presented is the novel in users' application algorithm, the purpose of which is to optimize bandwidth for first responders applied in the PPDR project

under grant agreement EU FP7 SEC PPDR-TC. This algorithm is responsible for incorporating more users and different levels of background load to a hybrid network. The proposed method analyses both positive and negative outcomes based on the results obtained. This algorithm has been presented in the PPDR project.

Declaration

I declare that the material presented in this thesis consists of original work undertaken solely by myself and whenever work by other authors is referred to, it has been properly referenced. The material has not been submitted in substantially the same form for the award of a higher degree elsewhere.

Juwita Mohd Sultan

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List of Publications/ Contributions

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Journals:

1. D. Zvikhachevskiy, J.M.Sultan, K.Dimyati, "Quality of Service Mapping Over WiFi+WiMAX and WiFi+LTE Networks", in *Journal of Telecommunication Electronic and Computer Engineering (JTEC)*, Vol 5 No 2, 2013.

2. J. M. Sultan, G. Markarian, and P. Benachour, "WiMAX Quality of Service Deployment in Disaster Management," in *International Journal of Advances in Computer Networks and Its Security (IJCNS)*, Vol 5, Issue 1, ISSN 2250-3575, 2015.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

AAS- Adaptive antenna system

AMC- Adaptive Modulation and Coding

AP- Access Point

ASN GW- Access Service Network Gateway

ATM- Asynchronous Transfer Mode

BE - Best Effort

BPSK- Binary Phase Shift Keying

BS- Base Station

BSHC- Base Station Hybrid Coordinator

BSS- Basic Service Set

CCA- Clear Channel Assessment

CID- Connection Identifier

CoS - Class of Service

CS- Convergence Sublayer

CCK- Complementary Code Keying

CPS- Common Part Sublayer

DCPCC- District Civil Protection Coordination Centre

DHCP- Dynamic Host Configuration Protocol

DL- Downlink

DS- Distribution System

DSL - Digital Subscriber Line

DSSS - Direct Sequence Spread Spectrum

ertPS - Extended Real time Polling Service

ESS- Extended Service Set

ETSI - European Telecommunications Standards Institute

EU- European Union

FEC- Forward Error Correction

FFT- Fast Fourier Transform

FHSS - Frequency Hopping Spread Spectrum

FTP - File Transfer Protocol

FDD- Frequency Division Duplex

3GPP- 3rd Generation Partnership Project

GBR - Guaranteed Bit Rate

GUI - graphical user interface

GHz- Gigahertz

HD- Half Duplex

HN - Hybrid Networks

HSDPA- High-Speed Downlink Packet Access

HSDPA+- Evolved High-Speed Packet Access

ID- Identifier

IEEE - Institute of Electrical and Electronics Engineers

IEEE-SA - IEEE Standards Association

IP - Internet Protocol

IR- Infrared

ISM- Industrial, Scientific and Medical

ISO- International Organization for Standardization

ITU- International Telecommunication Union

LB- Load Balancing

LLC- Logical Link Control

LMR- Land Mobile Radio

LOS- Line-of-Sight

LTE - Long Term Evolution

MAC - Medium Access Control

MANET- Mobile Ad-Hoc Network

MHz- Megahertz

MPDUs- MAC Protocol Data Units

MPEG- Moving Picture Experts Group

Mbps - Megabits per second

MIMO - Multiple Input Multiple Output

Mstr- Maximum Sustained Reserve Traffic Rate

Mrtr- Minimum Reserved Traffic Rate

MS- Mobile Station

Non-GBR - Non-Guarantee Bit Rate

NLOS- Non Line-of-Sight

nrtPS - Non-real time Polling Service

NS- Network Simulator

OFDM - Orthogonal Frequency Division Multiplexing

OFDMA- Orthogonal Frequency-Division Multiple Access

PCMCIA- Personal Computer Memory Card International Association

PHY- Physical Layer

PHS- Payload Header Suppression

PLCP- Physical Layer Convergence Procedure

PLR- Packet Loss Ratio

PMD- Physical Medium Dependent

PMP- Point to Multipoint

PPDR- Public Protection and Disaster Relief

PS- Privacy Sublayer

OSI- Open Systems Interconnection

QAM- Quadrature amplitude modulation

QCI - QoS Class identifier

QCI - QoS Class identifier

QoS - Quality of Service

QoE- Quality of Experience

QPSK- Quadrature Phase Shift Keying

REDComm- Rapid Emergency Deployment Mobile Communication

RLC- Radio Link Control

rtPS - Real Time Polling Service

SS – Sub-Station

SC- Single Carrier

SCA- Software Communication Architecture

SDR- Software Defined Radio

SDU- Service Data Units

SMC- Signal Modulation Scheme

SNR- Signal to Noise Ratio

SNMP- Simple Network Management Protocol

SLA- Service Level Agreement

TC- Transformation Center

TDD- Time Division Duplexing

TDMA- Time Division Multiplexing

TCP - Transmission Control Protocol

TETRA- Terrestrial Trunked Radio

TFTP- Trivial File Transfer Protocol

UL- Uplink

UGS- Unsolicited Grant Service

UMTS - Universal Mobile Telecommunications System

VLAN- Vitual Local Area Network

VoIP - Voice over IP

VPN - Virtual Personal Network

WEIRD- WiMAX Extensions for Remote

WiFi - Wireless Fidelity

WiMAX - Worldwide Interoperability for Microwave Access

Wireless MAN - Wireless Metropolitan Area Network

WLAN - Wireless Local Area Network

Chapter 1: Introduction

Deployment of various wireless broadband access networks has always been associated with the increasing demand for reliable and high speed access and also guaranteed quality of service (QoS). Typically, this is accomplished with different wireless system and also by different service providers. While each of the developed networks have well defined advantages, independent operation of these networks results in certain drawbacks [1][2]. In order to achieve the maximum benefit from the existing infrastructure, convergence of the networks is no more an option. However, such a proposal will not be successful without developing and providing the much needed end-to-end quality of service in the existing service classes across the proposed network architecture.

In this thesis, we propose approaches that utilize the hybrid broadband communication networks enhanced with prediction capabilities.

1.1 Motivation

Providing the required end-to-end QoS in hybrid networks is an arduous task due to the different bit rate, channel characteristics, bandwidth allocation, fault tolerant levels and handoff supports and methods implemented in each sub-network [3][4]. These differences can be outlined as below [5];

Wireless Local Area Networks (WLANs) provide higher data rate at a lower cost, but only within a limited area [6]. Worldwide Interoperability for Microwave Access Networks (WiMAX) coverage is up to 50km in radius with high data rates, good quality of service, seamless mobility both within a network and between networks of different technologies and service providers [7]. In Long Term Evolution (LTE) network, the traffic volume per subscriber increases rapidly as multiple services, for example voice, video, and data may be carried on multiple network domains, each with its own traffic pattern and QoS requirements [8] .

However, in many practical applications, users rarely use a homogeneous network because hybrid networks allow greater flexibility in working toward the desired results. At the same time, using hybrid networks generate a problem of parameter matching and optimization of end-to-end parameters for the entire hybrid network [9]. While individual standards do provide recommendations for optimization of key parameters, these recommendations are not valid in the integrated hybrid architecture. This problem is more intense when hybrid networks are intended in emergency disaster situations, such as earthquakes, tsunamis, flooding or forest fires. Such situations in which hybrid networks are used to address emergency disaster situations are the main subject of our research.

The end users' (user in different network connected seamlessly with other network) requirement could not be fulfilled if QoS guarantee could not be provided by the system, therefore, an end-to-end QoS for hybrid wireless networks needs to be defined. A comprehensive explanation will be discussed in Chapter 3 of this thesis. Due to the extensive number of possible hybrid network architectures, a common approach and optimization are required. For our condition, we narrowed the issue by concentrating on wireless fidelity (WiFi) and WiMAX as a hybrid network and optimizing parameters that are essential for these systems; throughput, delay, packet loss.

Our investigation has revealed that this field of research includes many open challenges, and we decided to address these problems by considering together hybrid wireless networks and QoS algorithms for first responders in emergency situations. During the research period, I was also involved in the European Union (EU) project, -focusing on the hybrid systems for Public Protection and Disaster Relief (PPDR) operations. My main role in the team was to prepare the simulation results which the investigation outcomes would benefit their operations as well. PPDR is one of the most important organizations which was responsible for the disaster preparedness and recovery. Conventionally it would assist the emergency communications among the first responders on site including the firefighters, emergency response personnel, law enforcement and also disparate agencies.

1.2 Objectives of the Thesis

The main objective of this thesis is to develop an optimization integration of WiFi and WiMAX model to be applied in the PPDR operations. The thesis also has specific objectives:

i) To improvise the QoS and providing the guaranteed of QoS in the context of disaster recovery, therefore increase the chances of survival.

ii) To evaluate the new approach on utilizing WiMAX network resources with the provided practical guidance.

1.3 Contribution of the Thesis

The contributions of the thesis can be summarised as follows:

i) It introduces a novel approach based on the parameters for two different hybrid networks; WiFi + WiMAX and WiFi + LTE by developing the end-to-end QoS mapping tables.

ii) Proposes a new approach based on WiMAX network with new QoS mapping. New scenarios are created with the new QoS mapping, and simulation results are presented. It was proven that the best QoS class in some scenarios did not provide the best parameters for users in the system.

iii) Proposes a new model of a hybrid system to optimize a chosen parameter in disaster management systems. An optimization model was developed and explained.

iv) Develops a novel users' application algorithms based on the PPDR operations requirements for hybrid networks. It applies the proposed algorithm to minimize delays and packet drops.

Commented [ez1]: Is packet dropped a term? If so, retain dropped and delete drops.

v) Provides a new model of a hybrid system analysis, applied to the PPDR operations in disaster management.

1.4 Research Methodology

This section will provide details and sufficient ideas of the method used in the research. There are three main bodies used as our research guidelines consists of Theoretical, Simulation and Practical Part. Generally, for the Theoretical Part, we conducted literature reviews from all the trusted inputs such as conference papers, journals, magazines, books and others. The topic includes homogenous wireless broadband system and also hybrid system which would be our main contribution to the knowledge later on. The next process would be the Simulation Part. We plan to use the simulation tools to obtain the results, analyzing the outcomes before implement them in the real situation. Based on several simulation tools such as NS2, NS3, Matlab and Opnet, we decided to use Opnet in our research. Opnet is recognized for its high reliability since it provides powerful simulation capability for the study of network architectures and protocols which makes the simulation of real-life networks close to reality. The most important thing is all the modules needed in our research (homogeneous and hybrid modules) are accessible in Opnet. The last process is the validation process for all the results obtained which we define as the Practical Part. Several experts were involved in this part to prove the validity of the simulation results.Therefore, based on the feedback received, throubleshooting process were also simultaneously performed in order to have optimize results.

1.5 Thesis Outline

The thesis is organised as follows. In Chapter 2, the overview of WiMAX and WiFi networks, hybrid broadband wireless networks and the difference between WiMAX and WiFi and system architectures are established in this chapter. Also, literature reviews are presented and the primary existing problems highlighted.

Chapter 3 discusses the QoS mapping table for WiFi, WiMAX and LTE. The chapter begins with a brief discussion on the QoS classes in WiFi, WiMAX and LTE. Following this, the parameters including measuring QoS are clarified. QoS mapping tables are also proposed and described here. Simulations were then conducted to test and verify the correctness of the mapping table. Herein, research was involved with WiFi, WiMAX and LTE, however, as we narrowed down our research, we focused only on WiMAX and WiFi as discussed in the next chapter.

Chapter 4 then discusses the simulation tools used in WiMAX. The simulation environment in Optimized Network Engineering Tool (OPNET) is first discussed, followed by the components accessible for WiMAX and WiFi modules. Then a WiFi/WiMAX gateway or also known as Customer-premises equipment (CPE), is explained its use to allow interoperability between WiFi and WiMAX as a hybrid network. Next, the evaluation of WiMAX system is conducted, particularly in disaster situations. Two scenarios are presented here to evaluate the performance.

In Chapter 5, the cross system for WiFi and WiMAX system by means of integration of WiFi and WiMAX, mainly focussing on the PPDR operation, is presented. During this research, I was involved in the EU project organized by the PPDR Transformation Center (TC). Therefore, my task was to prepare the simulation results based on the given scenarios. The layout for each scenario, based on PPDR requirements, was prepared by the engineers of Rinicom LTC Consortium. On top of that, I had to investigate and propose the best/optimum results which in future will be used as the EU standard and also used by the first responders in any emergency situation.

In Chapter 6, the optimization across different systems proposed in this chapter was extended to the PPDR operations. The focus was on optimizing the bandwidth utilization with more users and heavy applications added so that the end-to-end QoS in terms of delay, packet loss and minimum rate requirements will still be guaranteed. This chapter first discusses on the simulation results obtained based on the specific scenario. Next, the analysis of the performance is illustrated. Then, the proposal to obtain cross-system optimization is elaborated followed by the evaluations using simulations.

Chapter 2: OVERVIEW OF WiMAX and WiFi

WiMAX is a standard based on IEEE 802.16 broadband wireless access metropolitan area technology, expected to deliver high quality broadband services. Meanwhile WiFi belongs to one of the WLAN family referred to as IEEE 802.11b designed for a short distance communication [10]. WiMAX is expected to provide up to 40 Mbps over a 50km area, whereas the maximum transfer speed for WiFi is 100 Mbps within 100m area [2]. Although WiFi is known as one of the wireless standards, there are certain differences between them; standard, data rate, transmission distance, operating frequency and QoS.

In this chapter, an overview of the IEEE 802.16 and IEEE 802.11 standards are provided. Although there are other wireless broadband systems such as UMTS/3G and LTE, we focused only on WiMAX and WiFi in this research. Therefore, in this chapter, we start with the description of the evolution of the standards, followed by the architectures for each system. Also, we explain briefly about the Open Systems Interconnection (OSI) Layer, focusing on the physical and Medium Access Control (MAC) layer, since its interconnection with QoS necessary.

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2.1 The IEEE 802.16 standards

Institute of Electrical and Electronics Engineers (IEEE) is a professional working group established in 1963 with the task of developing standards and maintaining functions through the IEEE Standards Association (IEEE-SA) [11]. IEEE 802 refers to a family of IEEE standards dealing with local area networks and metropolitan area networks specifically for networks carrying variable-size packets. The IEEE 802.16 is a series of wireless broadband standards written by IEEE in 1999 to develop standards for broadband wireless metropolitan area networks [12]. Although the 802.16 family of standards is officially called

WirelessMAN in IEEE, it has been commercialized under the name WiMAX by the WiMAX Forum industry alliance.

There are various versions of WiMAX standards; IEEE 802.16-2001, IEEE 802.16-2004, IEEE 802.16e-2005, IEEE 802.16-2009. IEEE 802.16-2004 is known as Fixed WiMAX and IEEE 802.16e-2005 is known as Mobile WiMAX [13] . 802.16m is an upgraded version of 802.16-2009 version and is referred to as WiMAX advanced, which is also a candidate for the 4G, in competition with the LTE Advanced standard [14].

Both Fixed WiMAX and Mobile WiMAX systems are used for broadband data communication. The fixed WiMAX system will have subscriber terminals located at a fixed place and Mobile WiMAX will have nomadic, portable and mobile capabilities [15]. Thus, in this thesis, both Fixed and Mobile WiMAX systems will be used which will be explained later in the next chapter. Fixed WiMAX system is applied to the Planned Event situation meanwhile Mobile WiMAX as nomadic access is designated for Unplanned Event situation.

WiMAX operates at frequency of 2-66 Gigahertz (GHz), which is divided into two parts: 2-11 GHz and 10-66 GHz [16]. The lower frequency band supports Non Line-of-Sight (NLOS) whereas Line-of-Sight (LOS) is supported in the upper frequency band. Since LOS and NLOS propagation are quite different, a standard that supports physical and medium access control (MAC) layer supports for both bands needed to be designed [17]. Thus, the scope of 802.16-2004 standard covers the specifications of these two layers in the OSI model.

2.2 The IEEE 802.11 standards

The IEEE 802.11 standard was developed by the IEEE 802.11 Working Group since 1991, where the first standard was published in 1997. The first IEEE 802.11 standard specification, referred to as IEEE 802.11-1997 in 1997 which was then the IEEE 802.11-1999 in year 1999 reflected mostly minor changes. The IEEE 802.11-1997 and 802.11-1999 standards included a single connectionless MAC and three physical (PHYs) namely Direct-Sequence Spread Spectrum (DSSS), Frequency-Hopping Spread Spectrum (FHSS) and infrared (IR)[18]. The supported transmission rate was only 1-2 Mbps with DSSS, FHSS and were defined to operate at the 2.4 GHz Industrial, Scientific and Medical (ISM) bands [19]. This first standard was also initially referred to as “wireless Ethernet” since it was designed to support wireless services in local areas.

Since then, many amendments have been made to enhance its technology such as higher speed, QoS support and security enhancement. For example, the first two amendments namely, 802.11a and 802.11b, defined new PHY amendments [20]. The IEEE 802.11a-1999 defined a new PHY based on Orthogonal Frequency Division Multiplexing (OFDM) operated in the 5 GHz band supporting up to 54 Mbps transmission rate. Meanwhile IEEE 802.11b-1999 defined a new PHY based on Complementary Code Keying (CCK) to operate in the 2.4 GHz ISM bands with transmission rate up to 11 Mbps [21].

The standardization of the IEEE 802.11a was completed in 1999, but it was only introduced into the market in 2002 due to implementation difficulties. However, at the same time the 802.11b was more attractive and widely deployed, especially when the 802.11a devices were more expensive than the 802.11b. Even worst for the 802.11a was in 2003, the extension of the 802.16b for the 2.4 GHz referred as IEEE 802.11g-2003. The rates defined in 802.11g are exactly the same as those of the 802.11a since the 802.11g uses the exact same transmission schemes as the 802.11a. Due to the backward compatibility requirements, the performance of the 802.11g in ideal environments was worst than 802.11a. However, it became popular later in 2003 since the 802.11g devices were lower cost and backward compatible with the widely deployed 802.11b.

Then is the evolving of MAC layer in 802.11. The 802.11e-2005 was introduced to support QoS for multimedia applications, scheduling and admission control mechanism and other new features. Later on, to overcome security threats, new encryption schemes, new authentication and key management schemes were introduced by 802.11i-2004. Some other amendments, including 802.11k to provide mechanisms to higher layers for radio and network measurements were made. Meanwhile, to increase the WLAN throughput, 802.11n was introduced which would specify mechanisms to increase transmission rates up to 600 Mbps operating at 2.4 GHz and 5 GHz ISM bands. Therefore, 802.11n was chosen in my research in order to get the optimum performance. Table 2.1 summarises the evolution of 802.11 standards.

Table 2.1: IEEE 802.11 PHY Standards [22]

Release Date	**Standard**	**Frequency Band**	**Bandwidth (MHz)**	**Modulation**	**Advanced Antenna Technology**	**Maximum Data Rate**
1997	802.11	2.4 GHz	20 MHz	DSSS, FHSS	N/A	2 Mbits/s
1999	802.11b	2.4 GHz	20 MHz	DSSS	N/A	11 Mbits/s
1999	802.11a	2.4 GHz	20 MHz	OFDM	N/A	54 Mbits/s
2003	802.11g	5 GHz	20 MHz	DSSS, OFDM	N/A	542 Mbits/s
2009	802.11n	2.4 GHz, 5 GHz	20 MHz, 40 MHz	OFDM	MIMO, up to 4 spatial streams	600 Mbits/s
2013	802.11ac	5 GHz	40 MHz, 80 MHz, 160 MHz	OFDM	MIMO, MU-MIMO, up to 8 spatial streams	6.93 Gbits/s

2.3 The Architecture of 802.16 system

WiMAX architecture, which is similar to a cellular architecture consist of one base station (BS) with one or more sub-stations (SSs). However, a WiMAX BS could cover up to 3,000 square miles (8,000 square km). Meanwhile a WiMAX receiver could be a standalone tower or a (Personal Computer Memory Card International Association) PCMCIA card inserted in devices [23]. There are two basic operational modes delineated by the IEEE 802.16 standard: point to multipoint (PMP) and mesh networks. In the PMP mode, the BS serves a set of SSs in a broadcast manner, with all the SSs receiving the same transmission from the BS [24]. In other words, each SS directly communicates with the BS through a single-hop link, which requires a LOS transmission range between the BS and all SSs. On the other hand, mesh mode allows the SS to communicate directly among each other and this traffic can be routed through other SSs, without the need of a BS [25]. The mesh topology could reduce deployment cost in NLOS environments, extend the network coverage, enable fast and flexible network configuration. In addition, when the channel conditions are poor due to link failures, using the routing protocol, the traffic can be routed resulting in high network reliability and availability. The communication path between the BS and SSs is bidirectional, namely uplink and downlink. Uplink path is where the traffic goes from the SSs to the BS, and the downlink, where the traffic goes from the BS to the SSs as shown in figure 2.1.

Figure 2.1: Downlink and uplink communication path [26]

2.4 The Open Systems Interconnection (OSI) Model

The OSI Model was developed by the International Organization for Standardization (ISO) in 1978. While working on a network framework, ISO chose to build up the seven-layer model [27]. The OSI model characterizes a networking framework to execute protocols in seven layers. Control is passed from one layer to the next, beginning at the application layer in one station, and continuing to the bottom layer, over the channel to the following station and back up the hierarchy [28]. OSI's seven layers are partitioned into two sets: application and transport sets as mention in Table 2.2. The application sets incorporates the application, presentation, and session layers; the transport sets incorporates the transport, network, data link and physical layers [29]. The OSI Model works in a hierarchy, appointing tasks to every one of the seven layers. Every layer is in charge of performing assigned tasks and transferring completed tasks to the next layer for further processing. Today, numerous protocols are produced based on the OSI Model working mechanism. The OSI model does not perform any functions in the networking process [30]. It is a theoretical framework so we can better understand complex interactions that are happening.

Table 2.2: OSI Models [31]

OSI Layers	**Task**	**Layers Set**
Application	Interacts with the operating system or application whenever the user chooses to transfer files, read messages or perform other network-related activities.	Application Set
Presentation	Takes the data provided by the Application layer and converts it into a standard format that the other layers can understand.	
Session	Establishes, maintains and ends communication with the receiving device.	
Transport	Maintains flow control of data and provides for error checking and recovery of data between the devices. Flow control means that the Transport layer looks to see if data is coming from more than one application, and integrates each application's data into a single stream for the physical network	Transport Set
Network	Determine the way that the data will be sent to the recipient device such as Logical protocols, routing and addressing.	

Data Link	The appropriate physical protocol is assigned to the data. Also, the type of network and the packet sequencing is defined.	
Physical	Defines the physical characteristics of the network such as connections, voltage levels and timing.	

The services and protocols specified in IEEE 802 maps to the lower two layers (Data Link and Physical) of the seven-layer OSI Model. It splits the OSI Data Link Layer into two sub-layers named Logical Link Control (LLC) and MAC. In this chapter, we will cover the discussion of the Physical Layer and also MAC Sublayer.

2.4.1 The Physical Layer

The physical layer, the lowest layer of the OSI model, is concerned with the transmission and reception between a device and a physical transmission medium [32]. This includes the electrical/optical, mechanical, and functional interfaces to the physical medium, transmission mode and network topology as bus, mesh, or ring [33].

Occasionally the specification for physical layer for 10-66 GHz frequency wave is called WirelessMAN SC (single carrier) with frequency division duplex (FDD) and time division duplex (TDD) support modes [34]. It is used for LOS propagation that can reach multiple miles with a focused beam antenna design. However, in order to support NLOS from the 2-11 GHz band, three new physical layer specifications were introduced [35]:

i. WirelessMAN-SCa: A single carrier modulated air interface (for frequency band of between 2 to 11 GHz).

ii. WirelessMAN-OFDM: A 256-carrier orthogonal frequency division multiplexing scheme. Multiple access of different SSs is based on time division multiplexing (TDMA) scheme.

iii. WirelessMAN-OFDMA: A 2048-carrier OFDM scheme. A subset of carriers is assigned to an individual receiver to provide multiple access.

The difference between WirelessMAN-SCa and OFDM module is that OFDM is more resilient to the multipath effect since it allows neighboring subcarriers to overlap and result in higher bandwidth efficiency. Meanwhile the differences between OFDM and OFDMA is organized into two dimension operators; time and frequency [36]. The collaboration between these two parameters allows for multiple access by arranging resources into subchannels for individual receivers allocation. OFDM is applied to NLOS propagation because of the simplicity of the equalization process for multi carrier signals and their natural immunity to multipath propagation [37]. Initially, WirelessMAN-OFDM is popular among the vendors due to the reasons of Fast Fourier Transform (FFT) and less stringent requirement for frequency synchronization compared to WirelessMAN-OFDMA. However, since the introduction of WirelessMAN-OFDMA, it is more preferred by the industry because of bandwidth efficiency [38]. It works by distributing subcarrier-group subchannels matched to each user to provide the best performance, meaning the least problems with fading and interference based on the location and propagation characteristics of each user [39].

Other features in PHY layer are [40]:

i. Adaptive antenna system (AAS); multiple antennas are used at the receiver and transmitter ends to increase the channel capacity by the focused beam antenna design towards users to achieve in-cell frequency reuse. Fully utilizing beams of the adaptive antenna system will also result in less required power. Besides that, signal-to-interference (SNR) ratio will increase through combining multiple signals coherently.

ii. Adaptive modulation : There are multiple different modulation schemes for the uplink and downlink path, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (QAM), 64 QAM, and 256 QAM with different coding rates. It provides a wide range of trade-offs data rate and robustness depending on channel conditions.

iii. Space time coding: applied in the downlink communication path as an optional feature to provide for space transmit diversity. The space time coding assumes that the base station is using two transmit antennas and one transmit antenna for the subscriber stations.

2.4.1.1 The Frame Structure

The downlink and uplink subframes, which make up a frame, are transmitted using either FDD or TDD techniques [41]. In FDD, the downlink and uplink sub-frames use different frequencies, whereas in TDD, both of them share the same frequency but are transmitted in different time slots. FDD is commonly used for 2G and 3G cellular networks. Meanwhile, WiMAX supports full-duplex FDD and half-duplex FDD (HD-FDD). The difference is that in full-duplex FDD a user device can transmit and receive simultaneously, while in half-duplex FDD a user device can only transmit or receive at any given time slot [42] . TDD requires only one channel for transmitting downlink and uplink sub-frames at two different time slots resulting in higher spectral efficiency than FDD. The ratio for downlink to uplink can also be adjusted dynamically besides the flexibility of handling both symmetric and asymmetric broadband traffic [43].

TDD is mostly implemented in WiMAX since it uses only half of FDD spectrum, hence saving the bandwidth use, is less complex and a cheaper option. General frame structures of both TDD and FDD systems are presented in Figure 2.2.

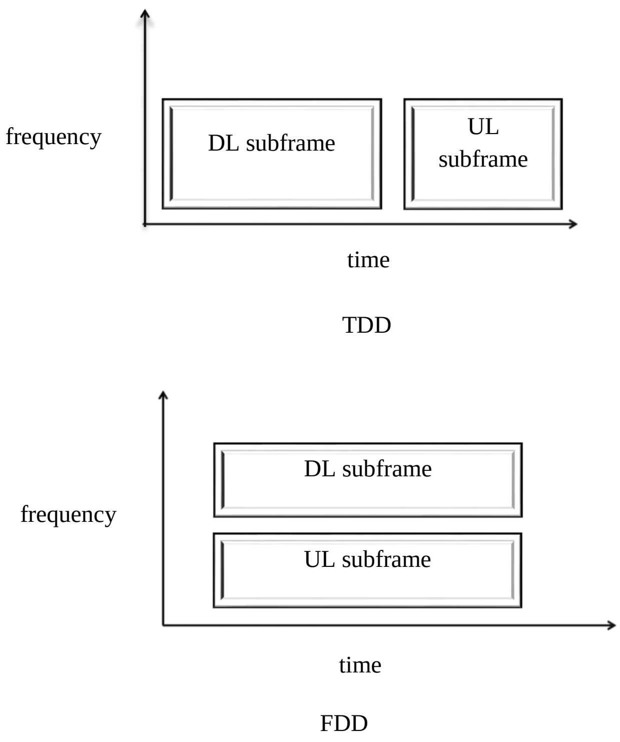

Figure 2.2: General frame structures of TDD and FDD systems

2.4.1.2 Adaptive Modulation and Coding (AMC)

WiMAX physical layer supports AMC to regulate the signal modulation scheme (SMC) depending on the signal-to-noise ratio (SNR) state of the radio link. When the radio link is of high quality, a peak modulation is used, thereby improving capacity [34]. During low SNR or fading conditions, the system switches to a lower modulation scheme, maintaining link stability and connection quality. The AMC is an important key feature in

WiMAX to maintain the quality of wireless transmission [44]. [44]. Table 2.3 summarises the modulation schemes and data rates supported by WiMAX that can be used to achieve various tradeoffs in data rate and robustness [45]. This means that transmission parameters such as modulation scheme, channel coding and forward error correction (FEC) settings can be changed on a per-SS basis. In terms of throughput, dynamic AMC allows the BS to trade off throughput for range. If a BS with the highest order modulation scheme 64QAM and a problem in connection with an SS is established, then modulation order is reduced to 16 QAM or QPSK modulation scheme which reduces throughput but increases effective range [44] [46].

Table 2.3: WiMAX modulation schemes and data rate [31]

Rate ID	Modulation rate	Coding	Receiver SNR (dB)
0	BPSK	1/2	N/A
1	QPSK	1/2	9.4
2	QPSK	3/4	11.2
3	16QAM	1/2	16.4
4	16QAM	3/4	18.2
5	64QAM	2/3	22.7
6	64QAM	3/4	24.4

2.4.2 The Medium Access Control Layer (MAC)

The MAC layer supports both LOS and NLOS operation by using TDMA technique, where users are assigned time slots accessing the uplink bandwidth channel based on the request/grant mechanism [47]. The predetermined service level agreement will facilitate different levels of QoS and bound the delay communication.

The MAC layer for 802.16-2004 is designed to support any present or future higher-layer protocol, for example, Internet Protocol (IP) versions 4 and 6, packetized voice-over-IP (VoIP), Ethernet, Asynchronous Transfer Mode (ATM), and virtual LAN (VLAN) services

[48]. Therefore, the MAC layer is separated into three sublayers namely the Convergence Sublayer (CS), the Common Part Sublayer (CPS) and the Privacy Sublayer (PS) as shown in Figure 2.3 [49] .

MAC Layer	Convergence sublayer (CS)			
MAC Layer	Common part sublayer (CPS)			
MAC Layer	Privacy sublayer (PS)			
PHY Layer	Transmission convergence sublayer			
PHY Layer	QPSK	16QAM	64QAM	256QAM

Figure 2.3: WiMAX MAC layer [50]

2.4.2.1 Convergence Sublayer (CS)

The CS is to classify and map service data units (SDUs) into the proper MAC connection using CID (connection identifier), preserve or enable QoS and enable bandwidth allocation. The sublayer supports two services; ATM and a packet convergence sublayer (which supports IPV4, IPv6, Ethernet, and VLAN). The additional function supported are payload header suppression (PHS) and reconstruction [51].

2.4.2.2 Common Part Sublayer (CPS)

The purpose of the CPS is to support the PMP connection from the BS with sectorized antenna to multiple SSs. It provides the core MAC functionality of system access, bandwidth allocation, connection establishment and maintenance [51].

2.4.2.3 Privacy Sublayer (PS)

The PS is accountable for the security of data that comes and leaves the PHY layer to ensure appropriate level of security for the parties involved in a transmission. This sublayer provides security features such as authentication, secure key exchange and encryption on the MAC Protocol Data Units (MPDUs) and forwards them to the PHY layer [52][50].

2.4.2.4 Connection Establishment

Since the 802.16 MAC is connection-oriented, a connection between an SS and a BS must be established before any user information can be sent. Using a connection-oriented MAC architecture, the uplink and downlink connections are controlled by the serving BS. The connection occurs between the MAC layer in the BS and MAC layer in the Mobile Station (MS) referred to as a unidirectional flow of data, with an assigned QoS [53]. Each connection is identified by a connection identifier (CID), which serves as a temporary address for the data transmission over the established link [35]. There are three types of connection in each direction defined for management purposes; basic, primary, and secondary connections [54]. The basic connection is used by the BS MAC and SS MAC to exchange short, time-urgent MAC management messages, which are not very delay tolerant. The same basic CID is assigned to both the downlink and uplink connections. It is also used for Radio Link Control (RLC) messages, which are used to control power and ranging in addition to changing burst profiles. The primary management connection is responsible by the BS MAC and SS MAC to exchange longer, more delay tolerant MAC management messages and its principle use is in the security sublayer [39] . The function of the secondary connection is to allow a particular protocol being run at a higher layer, for instance the routing protocol, to exchange their management messages, to transfer delay tolerant, and also standards-based messages [55]. Example of the standards are the Dynamic Host Configuration Protocol

(DHCP), Trivial File Transfer Protocol (TFTP), Simple Network Management Protocol (SNMP) [56]. Since secondary management messages are not MAC management messages, management connection is required only for managing the SSs.

2.4.2.5 Scheduling, Bandwidth Request and Grants

Each connection in the uplink direction is mapped to a scheduled service to improve the efficiency of the polling or granting process in the uplink bandwidth request [57]. The scheduling rules or policies which contain a set of parameters that quantifies the QoS requirements, are used by the BS while allocating bandwidth [58]. Using scheduling services at BS, bandwidth allocation is mainly characterized by their uplink bandwidth request and grant processes, which vary with traffic characteristics and delay requirements.

Bandwidth request is a mechanism that SSs uses to indicate to the BS that they need uplink band allocation. This band request message may be transmitted during any uplink allocation, except during any initial ranging interval [59]. Bandwidth can be requested by stand-alone requests (BW request MAC PDU) or a piggyback request. Table 2.4 lists a summary of the five different categories of scheduling services, including their individual application examples and attributes of bandwidth management. Piggyback request refers to a method of using a previously granted uplink channel access opportunity to inform the BS that an SS requires another allocation to send pending data. Meanwhile, bandwidth stealing refers to another special option, which uses the granted band for sending another band request rather than sending data [60]. Both of these special options for bandwidth requests are applicable depending on the scheduling type [58].

Table 2.4: Clasiffication of scheduling services [61]

Scheduling type	**Example**	**Piggyback request**	**Bandwidth stealing**	**Polling method**
Unsolicited Grant Service (UGS)	T1/E1 leased line, VoIP without silence suppression	Not allowed	Not allowed	PM bit used to request unicast poll for bandwidth needs on non-UGS connections
Real-time Polling Service (rtPS)	MPEG video	Allowed	Allowed	Only allows unicast polling
Non-Real-time Polling Service (nrtPS)	FTP	Allowed	Allowed	May restrict service flow to unicast polling through transmission/require policy: Otherwise all forms of polling are allowed.
Extended Real-time Polling Service (ertPS)	VoIP with silence suppression	Allowed	Allowed	All forms of polling allowed.
Best Effort (BE) Service	HTTP	Allowed	Allowed	All forms of polling allowed

Polling refers to the process of the BS allocating band to use as requested by SSs. In other word where the BS periodically allocates part of the uplink channel capacity that is issuing a grant or transmit opportunity in the uplink map to each SS that wants to send data. The bandwidth allocation can be done in two ways: individual SS or to a group of SSs which is also referred to as unicast polling and multicast or broadcast polling [62].

When unicast polling is made on an SS individually, no explicit message is needed to poll the SS. The SS is allocated with a bandwidth sufficient to respond to bandwidth request. Unicast polling is not made on the BS with UGS connection unless it signals by setting the

PM bit in the header to request additional non-UGS connection [63]. This saves bandwidth over polling all SSs individually. Multicast and broadcast polling are done when there is insufficient bandwidth to poll each SS individually. When polling is done in multicast, the allocated slot for making bandwidth requests is a shared slot, which every polled SS attempts to use or in other words to participate on contention resolution process [59]. Multicast polling is one of the mechanisms used in WiMAX networks, and achieves better and even guaranteed quality of service and with reduced waste in utilization [64]. Therefore, based on all the characteristics mention for each type of scheduling services, we narrowed our research into rtPS and BE scheduling type which will be discussed in Chapters 3 and 4.

2.5 The Architecture of 802.11 system

The main idea in our research is to build an integration sytem which focuses on WiMAX and WiFi network. Therefore, in this section, an overview of 802.11 system is added in this thesis. 802.11 is an evolving family of specifications for WLANs developed by IEEE [22]. The architecture encompasses of three layers: LLC, MAC, and physical layer [65]. In 802.11, each computer, mobile, portable or fixed device is referred to as a station. When two or more stations come together to communicate with each other, they form a Basic Service Set (BSS). A BSS consists of two stations executing the same MAC protocol and competing for access to the same shared wireless medium. The BSS may be isolated or it may connect to a backbone distribution system (DS) through an access point (AP). The AP may also function as bridge, meanwhile the DS can be a switch, a wired network, or a wireless network. The MAC protocol used in 802.11 architecture may be fully distributed or controlled by a central coordination system in the access point. Generally, BSS is known as a cell in the literature [66].

The simplest 802.11 configuration is where each station belongs to a single cell and within the range of the associated AP. It is also possible for two cells to overlap, therefore a single station could participate in more than one cell. The association between a station and a cell is a dynamic process where stations may turn off, in the coverage range or even out of the range. An extended service set (ESS) consists of two or more SS interconnected by a DS which will increase the network coverage [67].

2.5.1 The Physical Layer (PHY)

The 802.11 PHYs operate on unlicensed bands at 2.4 GHz and 5 GHz. Most of the PHYs which are DSSS, FHSS, 802.11b, and 802.11g operate at the 2.4 GHz, whereas 802.11a operates at the 5 GHz bands [68]. Modulation scheme used by 802.11 is TDD which is a similar concept used in typical cellular networks. The channel bandwidth is also dependent on the PHY's characteristics as 802.11a and 802.11g occupy a 20 MHz band while the 802.11b signals occupy a 22 MHz band [69]. The transmission rate for 802.11n covers up to 600 Mbps since it utilizes multiple antenna technologies (MIMO) and channel bonding (using 40 MHz bandwidth instead of 20 MHz) [70]. However, since the transmission rate is inversely proportional to the transmission range, therefore, the higher the transmission rate, the shorter the transmission range becomes. This is because to have a successful transmission, higher signal-to-interference-and-noise ratio (SINR) is needed for higher order modulation schemes. Table 2.6 lists a summary of the differences in 802.11 PHYs.

Table 2.6: Various PHYs of IEEE 802.11 [18]

PHY	Transmission schemes	Frequency bands	Transmission rates (Mbps) supported
Baseline	DSSS, FHSS and IR	DSSS, FHSS:2.4 GHz IR:850-950 nm	1.2
802.11a	OFDM	5 GHz	6,9,12,18,24,36,48,54
802.11b	CCK	2.4 GHz	5.5,11+ DSSS rates
802.11g	OFDM	2.4 GHz	6,9,12,18,24,36, 48,54 +802.11b rates
802.11n	OFDM, MIMO	2.4 GHz, 5 GHz	Up to 600

The IEEE 802.11 standard only deals with the two lowest layers of the OSI reference model, the physical layer and the data Link layer (or MAC layer) as shown in Figure 2.4.

<table>
<tr><td rowspan="2">Data Link Layer</td><td>LLC</td><td rowspan="2">MAC Management</td><td rowspan="4">Station Management</td></tr>
<tr><td>MAC</td></tr>
<tr><td rowspan="2">Physical Layer</td><td>PLCP</td><td rowspan="2">PHY Management</td></tr>
<tr><td>PMD</td></tr>
</table>

Figure 2.4: The 802.11 standards focus on the Data Link and Physical Layers of the OSI reference model [19]

The 802.11 Physical Layer is divided into two sub layers [71]:

i. The Physical Layer Convergence Procedure (PLCP) which acts as an adaption layer. The PLCP is responsible for the Clear Channel Assessment (CCA) mode and building packets for different physical layer technologies.

ii. The Physical Medium Dependent (PMD) layer specifies modulation and coding techniques. The PHY management layer takes care of the management issues such as channel tuning.

The Station Management sublayer is responsible for coordination of interactions between the MAC and PHY layers [72].

2.5.2 Medium Access Control Layer (MAC)

The MAC layer provides the functional and procedural means to transfer data between network entities and to detect and possibly correct errors that may occur in the physical layer. It also provides access to contention based and contention free traffic on different kinds of physical layers [72].

In the MAC layer, the responsibilities are divided into two sublayers namely: the MAC sub-layer and the MAC management sub-layer. The MAC sub-layer's task is to define the access mechanisms and packet formats meanwhile MAC management sub-layer is responsible for the power management, security and roaming services [73].

2.6 Wireless Hybrid Networks

Hybrid Networks (HN) are the most widely used types of communication system. HN is a network which unites different communication standards with different types of architectures. HN can be divided into the two main groups [9]:

- Hybrid networks based on two or more different networks architectures.
- Hybrid networks based on two or more different networks standards.

Usually three major types of network architectures are utilized in HN:

- Bus network architecture [1]
- Ring network architecture [2]
- Star network architecture [2]

These architectures are well-defined in literature and are not a subject of our research. We call them complementary and hierarchical. In our work we focus on HN utilizing different standards; hence our research will be based on the second type of HNs. Two main hybrid network topologies are widely used. A typical complimentary HN architecture is shown in Figure 2.5.

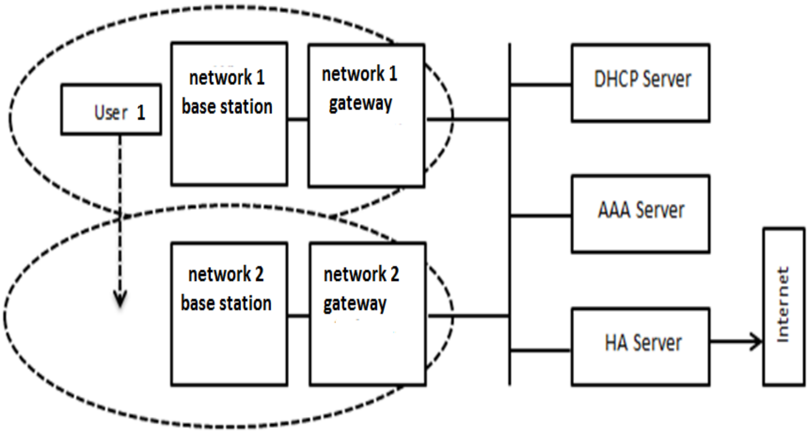

Figure 2.5: First hybrid network topology [9]

In this figure two networks compliant with different standards are interconnected in higher OSI layers, while each of the networks is directly connected to the Internet. At every instant, a user is connected to only one network, and one of the main functions of the HN is to support seamless roaming between the subnetworks. This type of an HN is used by mobile phone operators in which a user is constantly hopping between the 3G, High-Speed Downlink Packet Access (HSDPA), Evolved High-Speed Packet Access (HSDPA+) and other networks.

A typical architecture of the hierarchical hybrid network is shown in Figure 2.6. As the figure demonstrates, in this HN a user is permanently connected to both networks successively, although one network is used for connection on PHY layer, while the other is utilized as a backbone. A typical example of such an HN is a WiFi network connected to the Internet via WiMAX or LTE network.

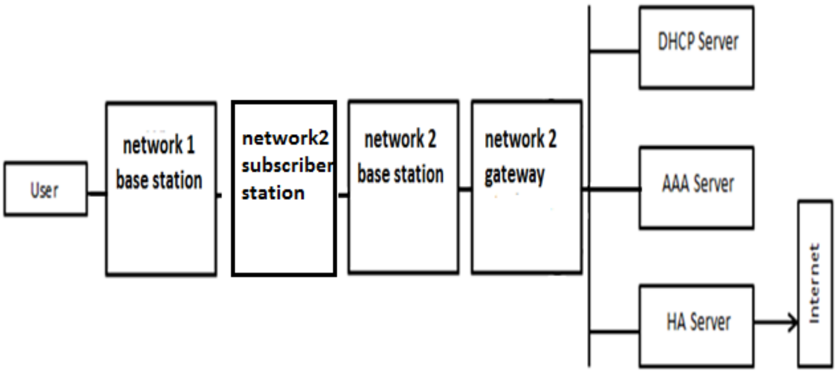

Figure 2.6: Second hybrid network topology [9]

The main evaluation parameters for hybrid networks are [74]:

- *Throughput* – the maximum data rate in a communication channel;
- *End to end delay* – the time taken for a data packet transmission from one user to another;
- *Latency* – a measure of the time delay between user and base station in the system;

- *Packet loss* –a parameter showing how many data packets were lost during the data transfer.

2.7 Backgound and Related Work

The subject of QoS allocation and management especially in hybrid network environment have become more challenging than ever due to the technological advances in wireless communication systems. Since mapping QoS in a hybrid system is not an easy task due to several factors, therefore; this area received great attention in the research community. In [3], the author proposed mapping method using Application Service Map (ASM) that classifies application services based on performance requirements. Using ASM method, new application could be easily inserted without the need of the alternation or modification. As in [75], a method of mapping QoS of UMTS and WiMAX over a loose coupling environment across IP based network is presented. A QoS gateway that will connect different wireless systems is used to support end-to-end QoS. Meanwhile, in [76], a thereotical explanation of end-to-end QoS over heterogenous networks was described . The EuQoS system architecture and protocol is used when there is a request from the user. One of the latest research [77], that maps WiMAX-WLAN-LTE using Load Balancing (LB) technique. The act of LB is as the load distributor for IP multimedia traffic across multiple servers which two or more servers can be incorporated. However, in the research, the QoS assigned to the users are not incorporated. For all the works mention in [63][64][65], there are no simulation results to verify the mapping methods. For this reason, we decided to work on two private networks first before moving on to bigger hybrid networks. In this thesis, we proposed QoS mapping tables for WiFi + WiMAX network and verifying it through the simulations results.

The other key components focus in this thesis, is the integration of WiFi + WiMAX hybrid systems for first responders in disaster or emergency situations. In [78], the discussion was dedicated to the problem arised in the WiFi+WiMAX interworking such as the protocols involved, the ideal QoS should be assigned when a user moves to a different network and others. Another concern in an integration system is the security and mobility issues as pointed out by the author in [79]. The paper presented a full system testbed to derive a unified security model and to support seamless handoff within a WiFi and WiMAX hybrid network. In [80], the research shows and end-to-end WiFi+WiMAX network deployment in testbed environment. Results obtained from the investigation indicates that WiFi+WiMAX deployment does not deteriote throughput as compared to a standalone WiMAX system. In [81], the author proposed an an analytic model for an integrated wireless network using WiMAX as backhaul support for WiFi traffic. Based on the research in [67], only the issues of WiFi+ WiMAX interworking was raised however no results was presented to support the problem statement. Meanwhile research in [68][68],as well in [70] that involves testbed environment, particularly only one parameters was considered in the network. To that reasons, in a different way, our work is focus on providing simulation results with consideration of all the QoS parameters and also on the optimization issues.

Other than that, since our research also involves with EU PPDR-TC Projects, some research have been done to support our work. A comprehensive explanation about the PPDR Projects will be explained in Chapter 5 of this thesis. There are diverse instances of system architecture for emergency mobile communications particularly in PPDR services either it is a standalone or a hybrid network. One of the examples of a standalone communication system is the satellite communications [82]. Satellite communication can provide a really wide coverage over a large area, which makes it very useful in specific and large natural disasters (earthquake, floodings). In spite of that, the limitation of satellite communication is the dependency on the ground infrastructure, which is associated with the management of the satellites. Thus, to serve with the localization and also to offer a continuous data link, an

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integration of satellite and aerospace communication segments with terrestrial backbones was introduced [83]. In [84], an emergency communication system based on software-defined radio (SDR) technology and software communication architecture (SCA) to support PPDR operations with special focus on the provision of satellite communications was presented. As well mention in [85], the research addressed the challenges of setting up satellite-based emergency communication facilities during a disaster from technical, financial and organizational standpoints. A research involving wireless mesh network is explained in [86], that proposed a mesh architecture as a back-up network in cases of emergencies and also measurement of the video streaming application as indicator of the network performance. Another research focus on PPDR operation is [87], which the author proposed an optimized mechanism for narrowband terrestrial trunked radio (TETRA) systems for intensive and concurrent voice usage and real-time, low-capacity data. It had also presented a scenario for evolution toward broadband land mobile radio (LMR) based on the design of communication systems that integrate TETRA and LTE radio access. One of the recent examples of an emergency network project is the Rapid Emergency Deployment Mobile Communication (REDComm) project [88]. REDComm foremost aim was to construct a communications infrastructure to bear out and handle communications in emergency and crisis situations, when standard communication networks are non usable.

However, our main focus for the PPDR project are the traffic combinations for the WiFi users in order to support more users in the hybrid network. Also, an optimization of the integration that minimizes the delays and packet loss and also with an optimum thoughput.

2.8 Summary

In this section we presented an overview of IEEE 802.16 and IEEE 802.11 standards, including a brief explanation on the systems layout. The 802.16 standard had evolved from its first version with some limitations in terms of line of sight communication and mobility to the latest version which improvised many aspects of the standard. Other than that, the evolution of the 802.11 was discussed for different standards and features. We identified several drawbacks for these systems and therefore explained the needs of hybrid network, hence providing a rationale for our research. We have presented different types of wireless hybrid network and some of the research related to hybrid network were also presented in this chapter as our reference for the rest of the research.

Chapter 3: QoS SUPPORT IN WIRELESS BROADBAND NETWORKS

Wireless communication has at present turned into an essential part in trading information, prompting more sharing resources among users and along these lines a bigger necessity of transfer speed in a system. Other than users' expense fulfillment with the wireless innovations, another vital component that has drawn an extraordinary arrangement is the ability of meeting QoS [89]. QoS is characterized as the capacity of a system to have some level of affirmation that its traffic and service necessities would be fulfilled in terms of packet loss, delay, throughput and jitter [90].

However, it would be different in the point of view of QoS in the disaster recovery. In times of catastrophe such as earthquakes or tsunamis, particularly when the major incumbent communications infrastructure was destroyed or damaged, a relatively tight and robust communications system needs to be deployed in order to support the communication needs of the rescue and retrieval operations. It is vital to have a guaranteed QoS to assist the communication needs among the first responders. Therefore, based on my proposed architecture, the QoS level could be increased and guaranteed, not only the aim is to communicate between the rescue team and the monitoring center but also important for saving lives.

In this chapter, the challenges of QoS connectivity are addressed and a novel QoS mapping scheme, particularly for hybrid broadband networks is proposed and assessed. We focused on two of the most widely used hybrid networks; WiFi-WiMAX and WiFi-LTE. As opposed to other works that were described and analyzed in Chapter 2, we worked with all possible QoS combinations for WiFi-WiMAX and WiFi-LTE hybrid broadband networks, and we will provide descriptions on how QoS maps can be developed based on the

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specifically chosen network parameter. This chapter starts with a brief discussion on the QoS classes in WiFi, WiMAX and LTE. Next, the parameters included in measuring QoS are clarified. Finally, taking after the proposed of our mapping algorithm, simulations are led to assess its performance.

3.1 Quality of Service in WLAN

WLAN provides convenience to physically move around and remain connected to the internet over local network. There are five main WLAN specifications: IEEE 802.11a, IEEE 802.11b, IEEE 802.11e, IEEE 802.11g and IEEE 802.11n [20][91]. Among them, the most popular standard is IEEE 802.11b which is also known as WiFi [92]. To assure a consistent QoS mechanism in WiFi network, the standard has categorized four priority classes, which are the voice, video, best effort and background as illustrated in Table 3.1 below. These QoS classes assure a consistent QoS mechanism across wired and wireless networks [91].

Table 3.1: WiFi QoS Classes [65]

QoS Classes	Description	Application
Real Time Polling Service (rtPS)	Bidirectional Voice calls with 64Kbps at 20ms. Talk spurt and silence spurt exponential with mean 0.35 seconds and 0.65 seconds.	Voice
	Downlink VBR stream with an average rate of 1Mbps and a peak rate of 5Mbps.	Video
Best Effort (BE)	Inter-page request time exponentially distributed of mean 15 seconds.	Web
	FTP download of a 20MB file	FTP

The four applications are categorized into 2 QoS classes; voice and video are listed in Real Time Polling Service (rtPS) classes; also known as the guaranteed bit-rate application, meanwhile the web browsing and file transfer protocol are classified in the Best Effort (BE) class or otherwise known as non-guaranteed bit-rate application.

3.2 Quality of Service in WiMAX

WiMAX protocol supports five different classes of service: Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Extended Real-time Polling Service (ertPS), Non-real-time Polling Service (nrtPS) and Best Effort Service (BE). These WiMAX QoS classes are listed in Table 3.2.

Table 3.2: WiMAX QoS [7]

QoS Classes	**QoS Specifications**	**Applications**
Unsolicited Grant Service (UGS)	Jitter tolerance Maximum latency tolerance Maximum sustained rate	VoIP
Real-time Polling Service (rtPS)	Traffic priority Maximum latency tolerance Minimum reserved rate Maximum sustained rate	Audio/Video Streaming
Extended Real-time Polling Service (ertPS)	Traffic priority Jitter tolerance Maximum latency tolerance Maximum reserved rate Maximum sustained rate	VoIP (VoIP with Activity Detection)
Non-real-time Polling Service (nrtPS)	Traffic priority Minimum reserved rate Maximum sustained rate	File Transfer Protocol
Best Effort Service (BE)	Traffic priority Maximum sustained rate	Data transfer, web browsing

i. *Unsolicited Grant Services (UGS):* This service is designed to support real-time service flows such as Voice over IP (VoIP), or for applications where WiMAX is used to replace fixed lines such as E1 and T1. It offers fixed-size grants on a real-time periodic basis, which eliminates the overhead and latency and assures that grants are available to meet the flow's real-time needs [8]

ii. *Real-time Polling Service (rtPS):* This service is designed to support real-time services such as Moving Picture Experts Group (MPEG) video. It is also used for enterprise access services where guaranteed E1/T1 rates are needed but with the possibility of higher bursts if network capacity is available. It has a variable bit rate but with guaranteed minimums for data rate and delay [9].

iii. *Extended Real-time Polling Service (ertPS):* This service is designed to support real-time services such as VoIP with silence suppression that have variable data rates but require guaranteed data rate and delay. One typical system in this QoS class is Skype [96].

iv. *Non-real-time Polling Service (nrtPS):* This service is designed to support for services where a guaranteed bit rate (GBR) is required but latency is not critical, such as File Transfer Protocol (FTP).

v. *Best Effort Service (BE)*: This service is designed for Internet services such as email and web browsing that do not require a minimum service-level guarantee. Data packets are carried as space becomes available. In this QoS class, delays may be incurred and jitter is not a problem [97].

3.3 Quality of Service in LTE

LTE was created by the 3rd Generation Partnership Project (3GPP) with the association of the European Telecommunications Standards Institute (ETSI). LTE is an arrangement of upgrades to the UMTS which was released in the 4th quarter of the year 2008 [12] while LTE-Advanced is an improvement of LTE which was affirmed as 4G standard by ITU Telecommunication Standardization Sector (ITU-T) in 2010 [13].

LTE standards indicate a bearer-level QoS model with a mixture of Class of Service (CoS)/QoS systems. In LTE QoS Model, each Evolved Packet System (EPS) bearer is connected with a QoS Class identifier (QCI) and an Allocation Retention Priority (ARP) [14]. EPS bearers can be characterized into two classes, which are the GBR bearers and Non-GBR bearers [13].

For GBR bearers, resources are forever apportioned amid a bearer's lifetime, which implies a certain bit rate is ensured. The suitable applications are VoIP and real-time video. While for Non-GBR bearers, there is no guarantee for resource availability and it is utilized for web browsing and file transfer applications [15]. There are nine levels of QCI in the LTE QoS as portrayed in Table 3.3. Each level of QCI is assigned to a different priority and applications. The advantages of LTE system with QoS is that it incorporates the priority handling, dedicated bandwidth, controlled latency, controlled jitter and improved loss characteristics [16].

Table 3.3: LTE QoS [17]

Resource Type	**Service**		**Example Service**
	QCI	**Priority**	
Guaranteed Bit Rate (GBR)	1	2	Conversational voice
	2	4	Conversational video (live streaming)
	3	3	Real time gaming

	4	5	Non-conversational video (buffered streaming)
Non-Guaranteed Bit Rate (Non-GBR)	5	1	IMS signaling
	6	6	Video (Buffered Streaming) TCP-based (e.g www, e-mail, chat, ftp, p2p file sharing, progressive video)
	7	7	Voice, Video (Live Streaming), Interactive Gaming
	8	8	Video (Buffered Streaming) TCP-based (e.g www, e-mail, chat, ftp, p2p file sharing, progressive video)
	9	9	

3.4 Parameters Involved in Measuring QoS

QoS is the most imperative parameter to examine in order to determine the quality of service over a network [18]. In this section, a brief explanation about the parameters used to investigate the QoS in a network is presented. With the end goal of that, the International Telecommunication Union (ITU) has set the computation and standard for the end-to-end delay, jitter, and throughput for real-time traffic to assure Quality of Experience (QoE) [19]. The execution measurements assessed in this research are:

3.4.1 Throughput

Throughput is an information's measure rate produced by the application or additionally determined as the ratio between the amount of data and the total amount of data transmitted by the system. It is measured in bits per second (bps) and normally applied to estimate the efficiency of a network [20].

$$\text{Throughput} = \frac{\sum \text{Packet Size}_i}{\text{Packet Arrival}_n - \text{Packet Start}_0} \qquad (3.1)$$

Equation 3.1 illustrates the calculation procedure to measure the throughput of packets. Packet Size_i is the packet size of the "i"th packet that arrived at the destination, Packet Start_0 indicate the period when first packet is transmitted, and Packet Arrival_n is the period when last packet arrived at the destination [21]. Details for each packets that reached the destination point, for example, the time a packet is transmitted, the time when the packet has arrived and the packet size were stored at the simulation log file [22]. Based on equation 3.1, to calculate the throughput, the size of each packet was included which gives the aggregate data that was transferred. The aggregate time was characterized as the distinction between the time the first packet started and the time the last packet reached the destination. Consequently, throughput is equivalent to the aggregate data transferred divided by the aggregate time it took in the communication link.

3.4.2 Average Delay

Delay or latency is the time required for a frame (packet) to travel from the source to its last destination. The delay sources can be described into transmission delay and destination processing delay, queuing delay, capacity calculation ineffective or insufficient, technological constraints and reordering packets [23]. Delay can be measured in either one-way or round-trip delay. Briefly, to get a general measurement of one-way delay, measure the round-trip delay and divide the result by two [108]. There is a sure least level of deferral that will be experienced because of the time it takes to transmit a packet serially through a connection. IP network delays can extend from only a couple milliseconds to a few hundred milliseconds [109]. The delay tolerated for real-time applications such as VOIP is up to

150ms before the quality of the call is unacceptable [108]. The lower the value of delay means the better performance of the protocol.

$$\text{Average Delay} = \frac{\sum \text{Packet Arrival}_i - \text{Packet Start}_i}{n} \qquad (3.2)$$

Equation 3.2 depicts the calculation method for measuring average delay. Packet Arrival_i means the period when packet "i" arrive at the destination while for Packet Start_i, is the period when the packet "i" leaves the source. The total number of frame or packets is indicated as "n" [14].

3.4.3 Average Jitter

Jitter is characterized as variety in delay after some time from point-to-point . It is ordinarily utilized as an indicator of consistency and stability of a network [110]. Jitter is a standout amongst the most essential components to determine the execution of a system and the QoS of the system. For instance in a VoIP call, if the delay of transmission changes too broadly, the call quality will be significantly debased. The measure of jitter tolerable on the network is influenced by the depth of the jitter buffer on the system equipment in the voice path [111]. The more jitter buffer available, the more the system can lessen the impacts of jitter. Equation 3.3 characterizes the steps to figure average jitter. It is the average of the absolute difference in the time it took for successive packets to achieve the destination [105].

Average Jitter

$$= \frac{\sum_i [(\text{Packet Arrival}_{i+1} - \text{Packet Start}_{i+1}) - (\text{Packet } Arrival_i - \text{Packet Start}_i)]}{n-1} \qquad (3.3)$$

3.4.4 Packet Loss

Packet Loss Ratio (PLR) means the quantity of packets lost amid the transmission from source to destination [112]. A few reasons for packet loss or corruption would be bit errors in an incorrect wireless network or inadequate buffers because of network congestion when the channel becomes overloaded [7]. Some of the packets are lost because of network congestion or due to noise. The estimation of PLR ought to be kept to least minimum as indicated by ITU standards since packet loss influences the apparent nature of the application. The lower estimation of the packet lost means the better execution of the protocol [105].

$$\text{Packet Loss Ratio} = \frac{\sum i \text{ Packet Loss}}{\text{iPackets Sent}} \qquad (3.4)$$

Equation 3.4 demonstrates the procedure to figure out the packet loss, which is characterized as the aggregate of all the packets that do not reach the destination over the total of the packets that leave the destination [3].

3.5 Mapping Table for WiFi, WiMAX, LTE

As one of the promising novel in future, to have the continuity for end-to-end in a hybrid network, these heterogeneous network classes should be adjusted together for a superior quality [113]. However as far as QoS is concerned, WiFi, WiMAX and LTE have diverse levels of QoS classes. For instance, two classes in WiFi, five classes in WiMAX while nine classes are in LTE. Since each network has distinctive level of QoS classes, the inspiration to have a consistent communication is entirely challenging. Accordingly, in this part, QoS mapping table for WiFi, WiMAX and LTE is introduced.

3.5.1 Proposed QoS Mapping Table for WiFi, WiMAX and LTE

The challenge of a communication is to have a smooth and ensured quality when users changed or move starting with one network then onto the next network [114]. In this research, the quality level for a hybrid network is been map that will have better throughput for both networks [115]. Table 3.4 delineates the QoS level for each of the networks.

Table 3.4: QoS classes in WiFi, WiMAX and LTE

	WiFi	**WiMAX**	**LTE**
QoS levels /classes	Real time Polling Service (rtPS)	Unsolicited Grant Service (UGS)	Real time Polling Service (rtPS)
	Best Effort (BE)	Real-time Polling Service (rtPS)	Best Effort (BE)
		Extended Real-time Polling Service (ertPS)	
		Non-real-time Polling Service (nrtPS)	
		Best Effort Service (BE)	

Therefore, we begin by creating and analyzing two practical cases, which are WiFi+WiMAX hybrid network and WiFi+LTE hybrid network.

3.5.1.1 QoS Mapping for WiFi+WiMAX Network

Figure 3.1 shows the diagram of the hybrid WiFi+WiMAX network. In this figure, we considered the most generic case when up to *M* WiFi users could be connected to any of the *N* WiMAX Client Premises Equipment (CPE). Such an architecture covers a wide range of applications, from basic internet browsing to environmental monitoring to healthcare and security [116][117].

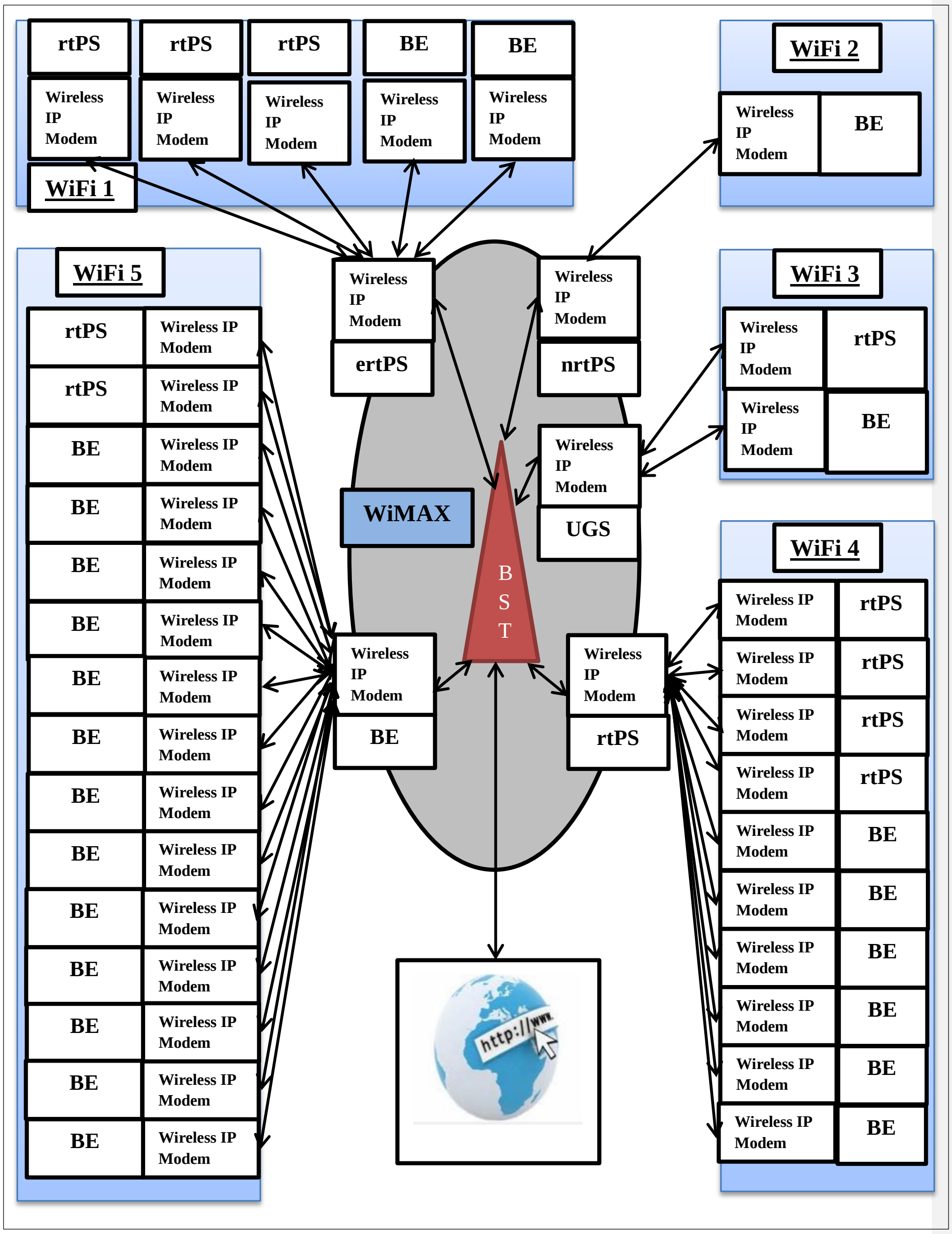

Figure 3.1: Hybrid WiFi + WiMAX network

Table 3.5 shows the proposed end-to-end QoS mapping in the above defined WiFi+WiMAX network. This mapping will be used in the analysis of the next section to ensure its ability to carry the required QoS.

Table 3.5: Mapping of WiFi to WiMAX QoS Classes

	Application Examples	**WiFi QoS Classes**	**WiMAX QoS Classes**
Real Time Applications	VoIP & Video conference Services	Real Time Polling Service (rtPS)	Unsolicited Grant Service (UGS)
			Real-time Polling Service (rtPS)
	Multimedia Streaming, Multiparty Gaming Services		Extended Real-time Polling Service (ertPS)
Non-Real Time Applications	Web browsing, File Transfer Services	Best Effort Service (BE)	Non-real-time Polling Service (nrtPS)
	MMS & Email Services		Best Effort Service (BE)

Table 3.5 shows the division process of 5 QoS in WiMAX into two separate sub – classes; Real Time Applications and Non-Real Time Applications. The UGS, rtPS and ertPS WiMAX QoS Classes are assigned to the Real Time Applications meanwhile nrtPS and BE are to the Non-Real Time Applications Sub-Classes. The process of these separations are based on the applications assigned to each WiMAX QoS Classes as illustrated in Table 3.2 which are based on real time and non-real time applications. Therefore, all the WiMAX QoS Classes in the Real Time Application Sub-Classes are mapped to the rtPS in the WiFi QoS Classes as shown in Table 3.5 as green colour. Whereas, the indicator of orange colour represents the remaining WiMAX QoS Classes which are nrtPS and BE that maps to BE in WiFi QoS Classes.

3.5.1.2 QoS Mapping for WiFi+LTE Network

Figure 3.2 shows the hybrid network architecture consisting of WiFi and LTE networks. This configuration is similar to the previous WiFi + WiMAX scenario; which in this case, there are 5 users in the LTE that are connected to 5 different WiFi scenarios.

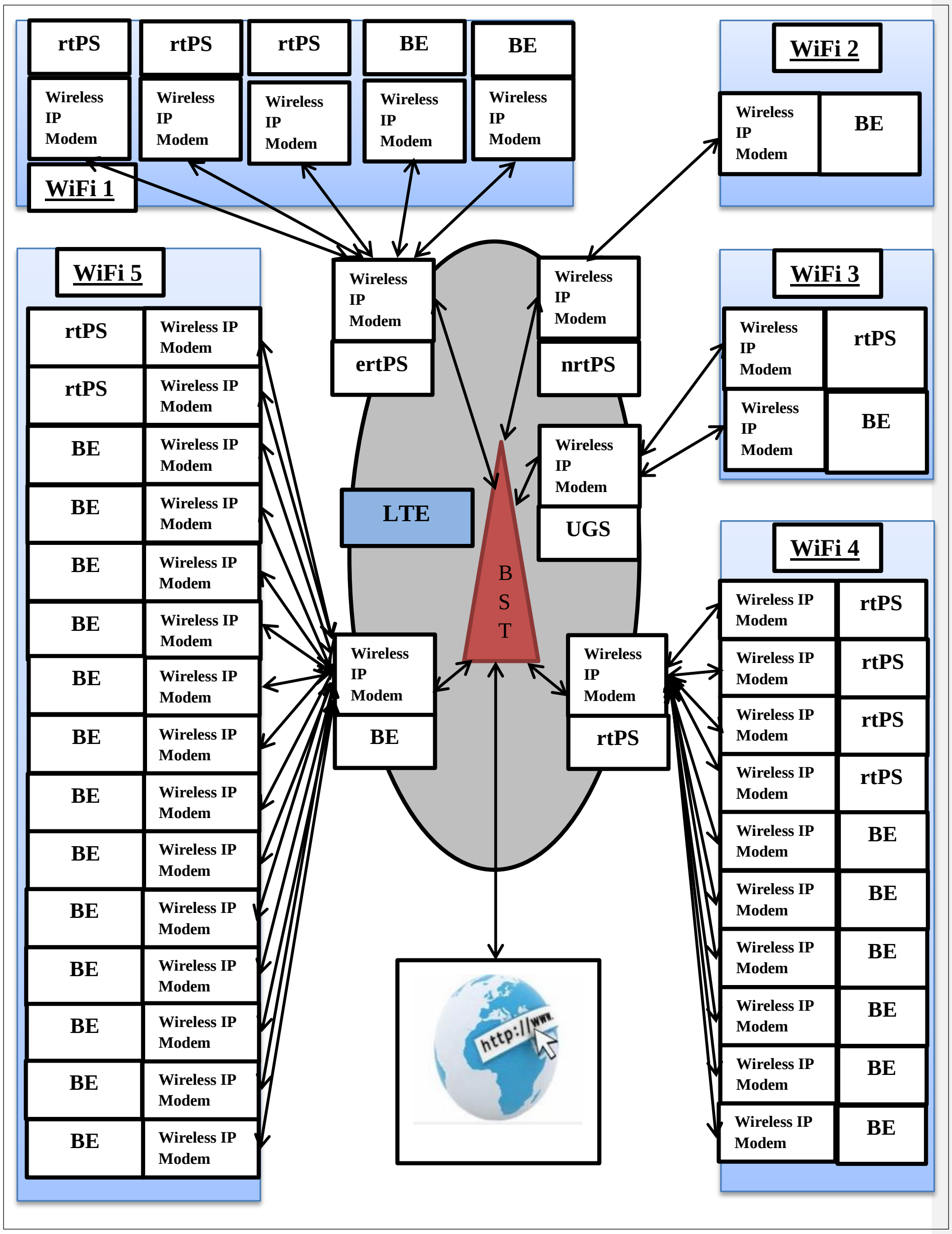

Figure 3.2: Hybrid WiFi+LTE network

Table 3.6 shows the proposed mapping for end-to-end QoS in WiFi+LTE Network. This mapping will be tested in the next section to ensure its ability to carry the required QoS.

Table 3.6: Mapping of WiFi to LTE QoS Classes

<table>
<tr><th>Resource Type</th><th>Application Examples</th><th>Wi-Fi Network</th><th>Resource Type</th><th colspan="2">LTE Network</th></tr>
<tr><td></td><td></td><td>Wi-Fi QoS Classes</td><td></td><td>LTE QoS Classes</td><td>Priority</td></tr>
<tr><td rowspan="3">Real Time Applications</td><td rowspan="2">VoIP & Video conference Services</td><td rowspan="3">Real Time Polling Service (rtPS)</td><td rowspan="3">Guarantee Bit Rate (GBR)</td><td>rtPS1</td><td>2 & 3</td></tr>
<tr><td rowspan="2">rtPS2</td><td rowspan="2">4 & 5</td></tr>
<tr><td>Multimedia Streaming, Multiparty Gaming Services</td></tr>
<tr><td rowspan="2">Non-Real Time Applications</td><td>Web browsing, File Transfer Services</td><td rowspan="2">Best Effort Service (BE)</td><td rowspan="2">Non-Guarantee Bit Rate (Non-GBR)</td><td rowspan="2">Best Effort Service (BE)</td><td rowspan="2">1,7,6,8 & 9</td></tr>
<tr><td>MMS & Email Services</td></tr>
</table>

3.5.2 Simulations

Numerous simulations representing various scenarios and different QoS mapping with reference to Table 3.5 and Table 3.6 were conducted using the Network Simulator 2 (NS2) and Network Simulator 3 (NS3) [118] simulation tools.

3.6 Results and Discussions

For the evaluation of the developed QoS mapping in WiFi+WiMAX and WiFi+LTE networks, the number of users were increased to the level when it affects the overall throughput in the network.

3.6.1 Hybrid Network for WiFi+WiMAX

The first hybrid network (WiFi+WiMAX) contains 5 users in WiMAX network with 5 different scenarios in the WiFi network as illustrated in Figure 3.1. The topology illustrates the downlink processing in which data or information from the base station is transmitted to the users in the WiMAX network. In this situation, these users can also function as a switch that acts as a hybrid connection with the WiFi network or users. As shown in Figure 3.1 above, the total bandwidth for all users in the WiMAX network is 40 Mbps which is around 22 Mbps allocated for BE QoS users, 15 Mbps for rtPS QoS users, and 3 Mbps for all the other remaining WiMAX QoS users. For the purpose of network optimization, therefore in this analysis, the discussion will only focus on the BE and rtPS QoS in WiMAX network which are WiFi4 and WiFi5 scenarios.

3.6.1.1 Scenario 1

In this scenario (WiFi4), total number of users in WiFi network is 10 where 4 users are with the rtPS QoS and 6 users are with the BE QoS. All of them are connected to the rtPS QoS in the WiMAX network. We chose 10 as the total number of users since it could not be more or less than the amount of bandwidth given which is 15 Mbps. Moreover, in this scenario, we would like to show that when a user with rtPS QoS in WiMAX network moved to a WiFi network, the user with BE QoS performed higher throughput compared to the user with rtPS QoS. From the results obtained, it showed that users with BE QoS in the WiFi network outstrip the users with the rtPS QoS in the same network. The throughput for each BE WiFi user is around 1.25 Mbps compared with 963.5 kbps for the rtPS WiFi users as shown in Figure 3.3 and 3.4. The outcomes are also valid with others combinations of users in the WiFi4 scenario such as when there maximum or minimum of rtPS users [9rtPS+1BE, or 1rtPS+9BE].

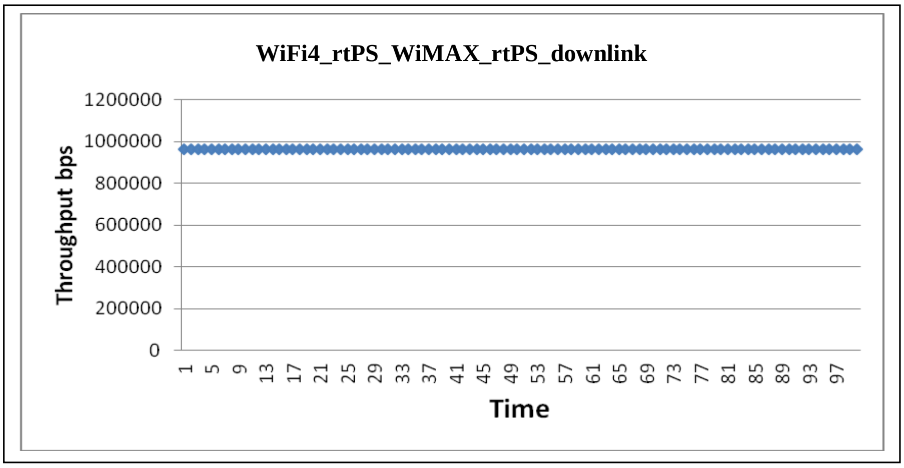

Figure 3.3: Throughput when rtPS for WiFi and WiMAX network

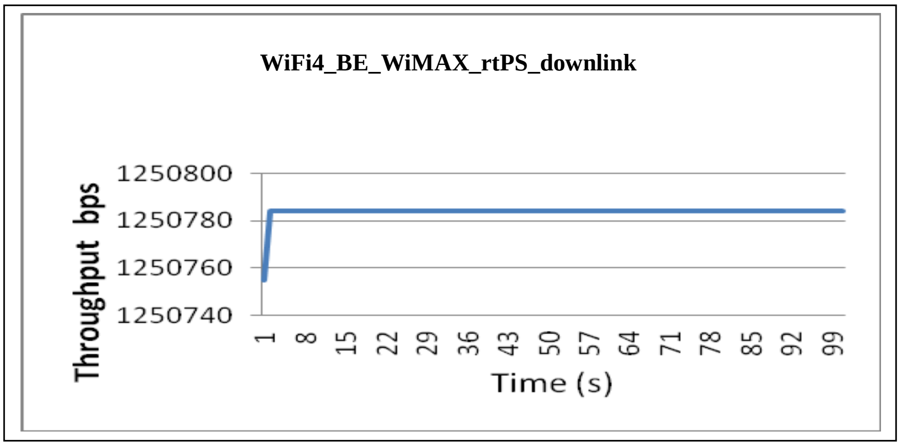

Figure 3.4: Throughput when BE for WiFi and rtPS for WiMAX network

3.6.1.2 Scenario 2

In this scenario (WiFi5), total remaining WiMAX bandwidth is 22 Mbps. Again, in this situation when a user in WiMAX with BE QoS moved to WiFi network, we wanted to like to show that the BE QoS will have higher data rate compared to the rtPS user. Therefore, we increased the total users to 15 which is less than the amount of the WiMAX bandwidth given. The number of users with the rtPS QoS in WiFi network is 2 and the remaining 13 users are for the BE QoS. They are connected to the BE QoS in the WiMAX network. Once again the throughput for the BE QoS users in WiFi network were much greater which is around 1.37 Mbps compared with 963 kbps for the rtPS QoS users as illustrated in Figure 3.5 and 3.6 below. The results are also valid with others combinations of users in the WiFi5 scenario such as when there is a maximum or minimum of rtPS user [14rtPS+1BE, or 1rtPS+14BE].

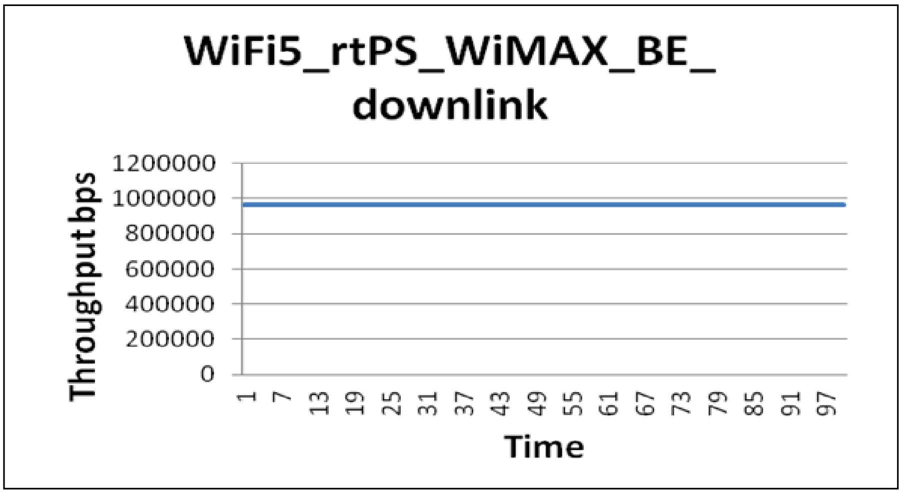

Figure 3.5: Throughput when rtPS for WiFi and BE for WiMAX network

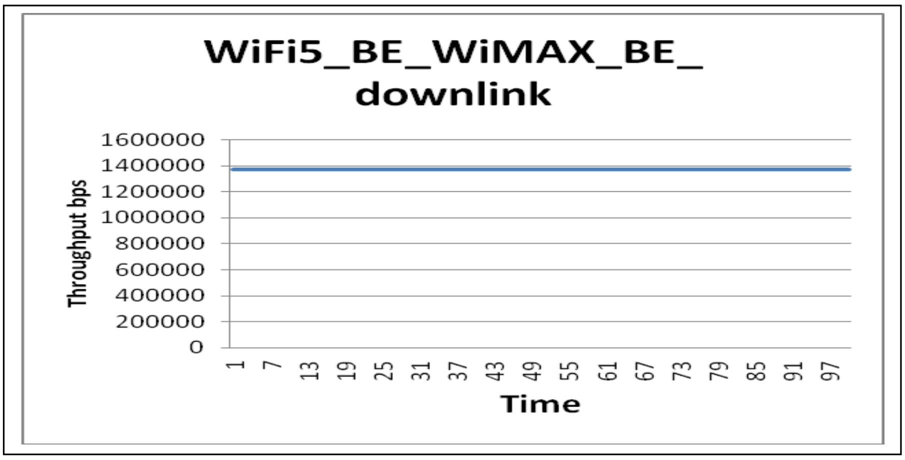

Figure 3.6: Throughput when BE for WiFi and WiMAX network

3.6.2 Hybrid network for WiFi+LTE

The second hybrid network (WiFi+LTE) caters for 5 users in LTE network with 5 different scenarios in the WiFi network as shown in Figure 3.2. As in WiFi+WiMAX, the topology also illustrates the downlink processing in which data or information from the base station is transmitted to the users in the LTE network. For this simulation, the total bandwidth for each user with the rtPS QoS in LTE network is assumed to be around 5 Mbps and for user with the BE QoS it is 30.8 Mbps. Similar to WiFi+WiMAX above, our focus here is also on the worst case scenarios which are WiFi4 and WiFi5 scenarios.

3.6.2.1 Scenario 1

This scenario is the same as WiFi4 scenario in WiFi+WiMAX hybrid model in which the total number of users in WiFi network is 10 where 4 users are with the rtPS QoS and 6 users are with the BE QoS. All of them are connected to the rtPS QoS in the LTE network. It can be seen from the results obtained that user with rtPS QoS in the WiFi network outperformed the users with the BE QoS in the same network. This is evident from the fact that each user with the rtPS QoS will occupy 1 Mbps throughput whereas the other 6 users with the BE QoS need to share the remaining 1 Mbps among themselves as shown in Figure 3.7 and 3.8.

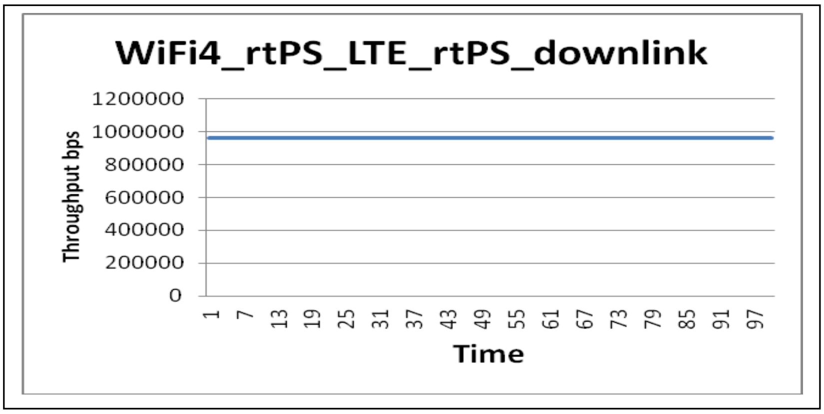

Figure 3.7: Throughput when rtPS for LTE and WiFi network

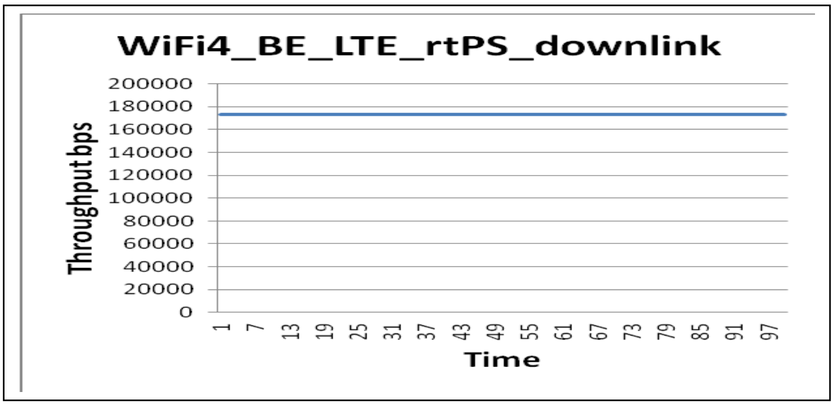

Figure 3.8: Throughput when BE for WiFi and rtPS for LTE network

3.6.2.2 Scenario 2

In this case (WiFi5), the total number of users in WiFi network is increased to 15. The number of users with the rtPS QoS in WiFi network are 2 users and the remaining 13 users are for the BE QoS. All users are connected to the BE QoS in the LTE network in which total bandwidth given is around 30.8 Mbps. The results show that users with BE QoS in WiFi network gain much higher throughput which is around 1.8 Mbps compared with 963 kbps for users with the rtPS QoS as evident from Figure 3.9 and Figure 4.0 and again it is attributed to the nature of best effort services.

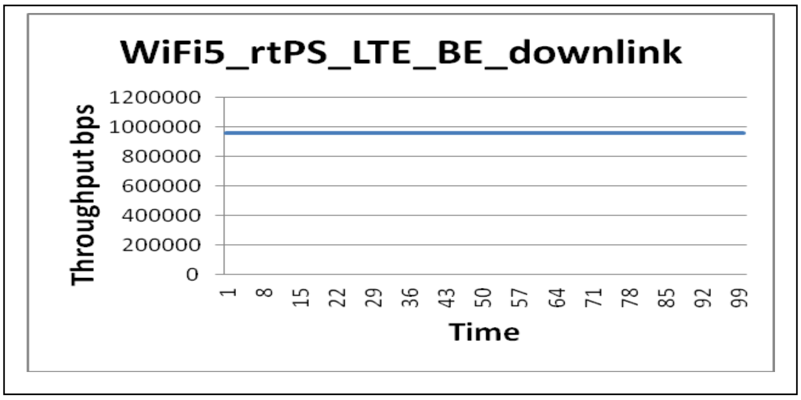

Figure 3.9: Throughput when rtPS for Wi-Fi and BE for LTE network

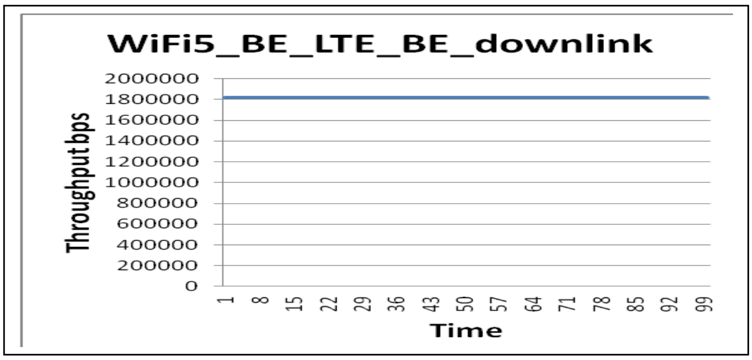

Figure 4.0: Throughput when BE for LTE and WiFi network

3.7 Summary

In this section, we have presented a new approach for designing QoS maps for hybrid networks particularly for two of the most widely used cases of hybrid networks: WiFi+WiMAX and WiFi+LTE. The main task of these models was to illustrate how the system parameters changed depending on information transmitted with the various QoS classes through a hybrid network. A major parameter in the functioning of the presented network is the users' throughput. The simulation provided us with the following conclusion:

- depending on the network load, the worst class of QoS priority can be the best option for the user. It was explained not only using theory but also by providing practical explanation with actual parameters of the hybrid network. This is due to the theoretical characteristic of the rtPS QoS, which is designed to support real-time service flow. In contrast, BE QoS is designed for non-real-time applications where no service guarantee is provided and therefore control services on a best available basis.

- Therefore, in order to accentuate the merit of the BE QoS, we investigated a variety of users' scenarios and validated them through simulations. Taking Scenario 1 and Scenario 2 for WiFi+LTE hybrid network for example, in this situation the LTE network will intuitively decide to connect the WiFi users with the LTE rtPS QoS. This is to ensure that all the WiFi rtPS users will have the best and stable throughput. However, this LTE rtPS switch/user can only manage to support up to 4 WiFi rtPS users or else there is no slot available for the WiFi BE user. Meanwhile if there is a large number of WiFi users, they have to be connected to the LTE BE QoS. This unique hybrid network can support up to more than 30 WiFi users where at this point the WiFi BE user's throughput is still better than that of the WiFi rtPS user.

- Hence, it can be concluded that although BE QoS is the cheapest pricing or probably the most unwanted QoS model, it still possesses satisfying network accomplishment.

- Throughput obtained for rtPS and BE QoS shown in the mapping tables indicates that:

Summary	**WiMAX bandwidth**	**Indicator**	**Users**
BE<rtPS	Total WiMAX bandwidth	<	Total number of users
BE=rtPS	Total WiMAX bandwidth	=	Total number of users
BE>rtPS	Total WiMAX bandwidth	>	Total number of users

Chapter 4: Simulation Environment

One of a cost-effective way of evaluating the performance of a system is by using a simulation process. The simulation procedures aim to investigate the behavior of the theoretical models in pre-defined and customized environments, and, if possible, to compare and contradict them with real data of live networks. Simulations may also shorten the time in getting the end results which may take longer time in a real-system. By employing the original parameter applied in a real-system, the simulation can be made simpler without scarifying to the correctness of the end results.

Commented [ez5]: I am unsure of what you mean here. I don't think scarifying is the appropriate term to use unless this is a technical term.

Since we are using the simulation tool for the previous and for next remaining chapters, in this section we will discuss the simulation tools accessible for WiMAX and WiFi. Followed by the description of Optimization of Network Engineering Tool (Opnet) Simulation Tool, which we used in our research. Next, we will present a layout on the simulation environment in Opnet and also the components accessible for WiMAX and WiFi modules in Opnet. Finally, we will illustrate the simulations conducted for WiMAX system particulary for a disaster management situation.

4.1 Simulation Tools for WiMAX System

There are several network simulation programs such as Qualnet, Network Simulation 2 (NS2), Network Simulation 3 (NS3) and Opnet modeler that can be used to simulate wireless network, including WiMAX network [119]. Each program differs from the other, both in terms of the ease and the ability to use with their own advantages and disadvantage. NS2 and NS3 are a discrete-occasion system test systems, basically expected for examination and instructive applications. NS3 is free programming, authorized under the GNU GPLv2 permit, and it is openly accessible for exploration, and improvement [120]. On the other hand, as one of the leading simulators for network research and development, OPNET [121] provides a powerful simulation capability for the study of network architectures and protocols. It is widely used in both industry and academia. Compared to another well-known simulator NS2 [118], OPNET has a well-engineered user- interface using mainstream software and operating system, which are attractive to network operators. Another reason to choose OPNET is the fact that it contains a vast number of models for commercially available network elements and has various real-life network configuration capabilities, which makes the simulation of real-life networks close to reality and it is recognized for its high reliability [122] . Therefore, in this chapter and mostly for all the projects involved in my research, I chose to use the Opnet Modeler 16.5 simulation tool for the simulation purpose.

4.2 Opnet Simulation Tools

Opnet is a research oriented network simulation tool that provides a development environment for modeling and simulation of deployed wired as well as wireless networks. It is otherwise called an exceedingly advanced simulation software package that enables developers to model communications networks and distribute systems, and provide multiple solutions for managing networks and applications such as network operation, planning, research and development (R&D), network engineering and performance management [123]. Opnet uses a hierarchical strategy to organize all the models to build a whole network and allows them to analyse the behaviour and performance of modelled systems through Discrete Event Simulations (DES) [124]. Other features of OPNET include graphical user interface (GUI) interface, comprehensive library of network protocols and models, source code for all models, graphical results and statistics, etc [106]. Some of the possible wireless communication technologies that can be simulated in OPNET are Mobile Ad-Hoc Network (MANET), 802.11, 3G/4G, Ultra-Wide Band, WiMAX, LTE, Bluetooth, and ZigBee [125].

Simulating a scenario can overcome constraints of proprietary hardware and software such as lack of development tools. Therefore, OPNET is of the most popular, accurate and applicable in the real world in the field of network simulation. Briefly, OPNET MODELER was selected, due to the following abilities [126]:

a) Provides a comprehensive development environment supporting the modelling of real life network configurations.

b) Performes discrete-event simulation tool with a convenient development environment.

c) Provides graphical user interfaces known as editors to capture the specifications of deployed networks, equipment, and protocols.

d) Opnet modeler has a library of models for most of the common networks around us.

e) This software is mostly used in the Research and Development (R&D) techniques for students, lecturers, engineers, and researchers.

A simulation in OPNET is divided into a three-tiered structure, namely: network model, node model, and process model as shown in figures 2,3, and 4 [106] . The top layer is the network layer that reflects the topology of the network, the middle layer is the node layer that is composed of the corresponding protocol models and reflects the characteristics of the equipment, and the bottom layer is the process model that is described by finite state machines. The three tier model fully corresponds to the actual network, protocol and equipment, and it can reflect the relevant characteristics of the network.

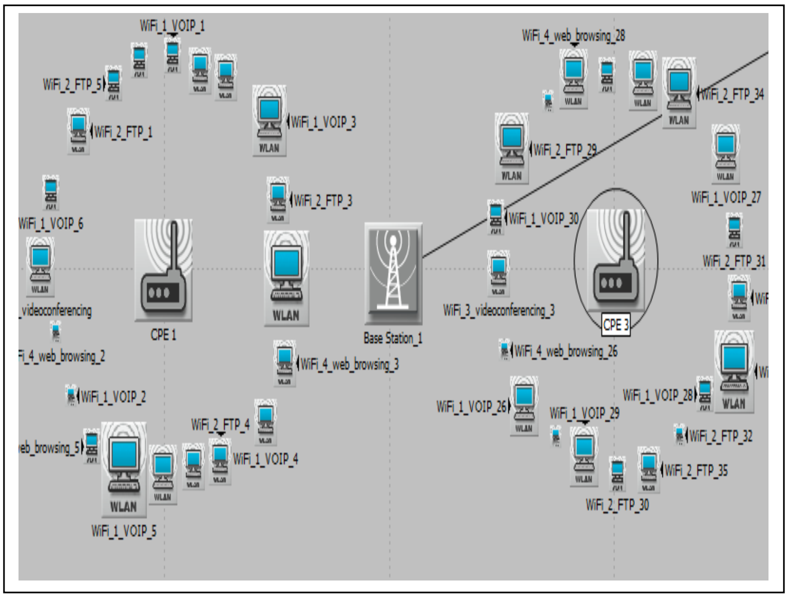

Figure 4.1: The Network Model

The Network model is the main staging area for creating a network simulation where user can build a network model using models from the standard library, choose statistics about the network, run a simulation, and view the results. Besides that, user can also create node and process models, build packet formats, and create filters and parameters, using specialized editors that can be accessed from the Project Editor [127].

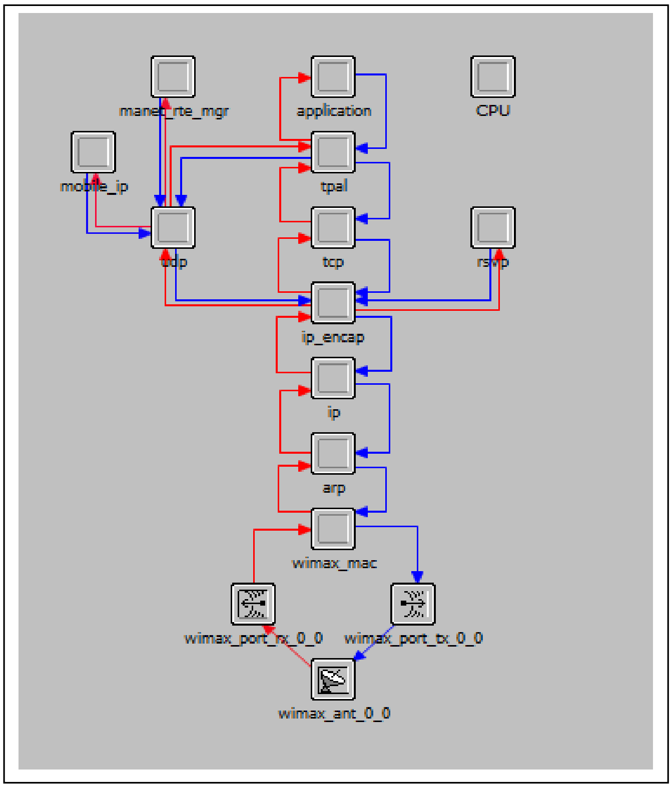

Figure 4.2: The Node Model

The Node model lets the user define the behavior of each network object. Behavior is defined using different modules, each of which defines some internal aspect of node behavior such as data creation, data storage, etc. Modules are connected through packet streams or statistic wires. A network object is typically made up of multiple modules that define its behaviour [128].

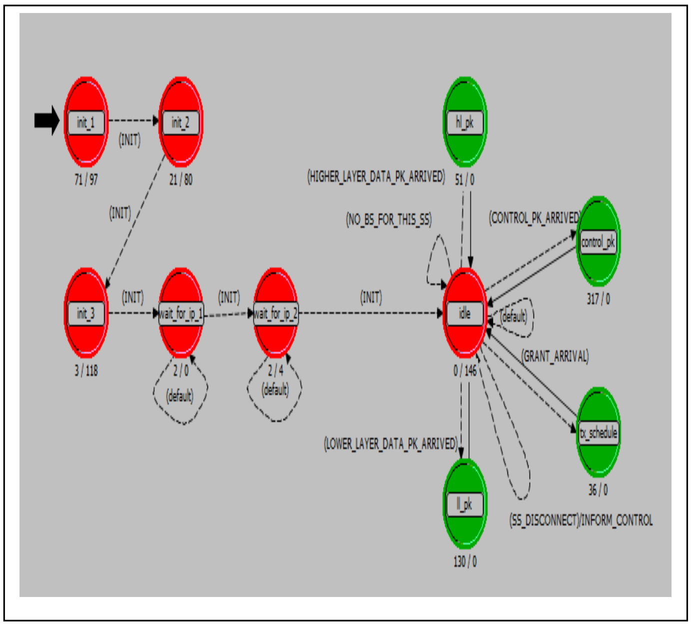

Figure 4.3: The Process Model

The Process model is used to create process models, which control the underlying functionality of the node models created in the Node Editor. Process models are represented by finite state machines (FSMs), and are created with icons that represent states and lines that represent transitions between states. Operations performed in each state or for a transition are described in embedded C or C++ code blocks [128].

4.2.1 Overview of the Opnet Simulation

The workflow to build a network model and run simulations [128].

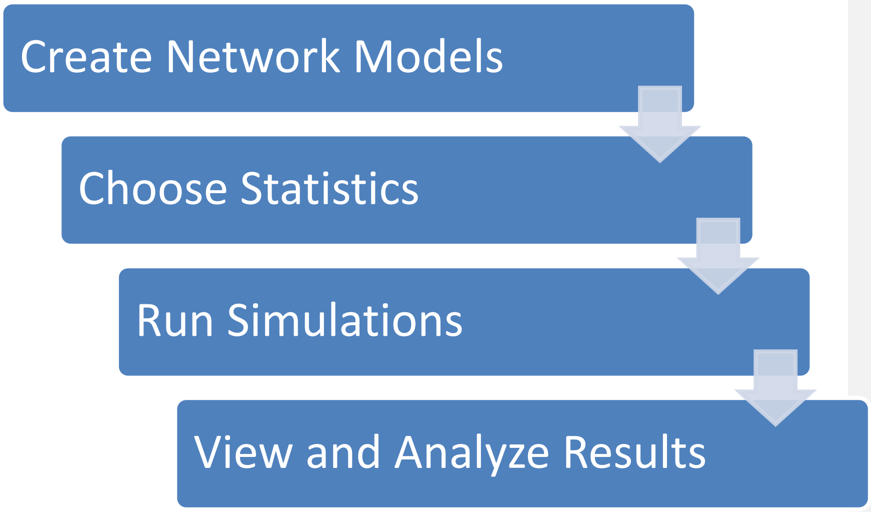

Figure 4.4: Opnet Simulation Workflow

The available wireless models in Opnet are LTE, WLAN, MANET, WiMAX, TDMA [129]. These models can be deployed either by using the wireless network deployment wizard or can be chose from the library itself. Once a file for a new project is opened, a few parameter settings need to be done such as the Network Creation, Location, Technology to be used, Topology, Node Mobility and lastly the Configuration Summary [130] as depicted in Fig 4.5.

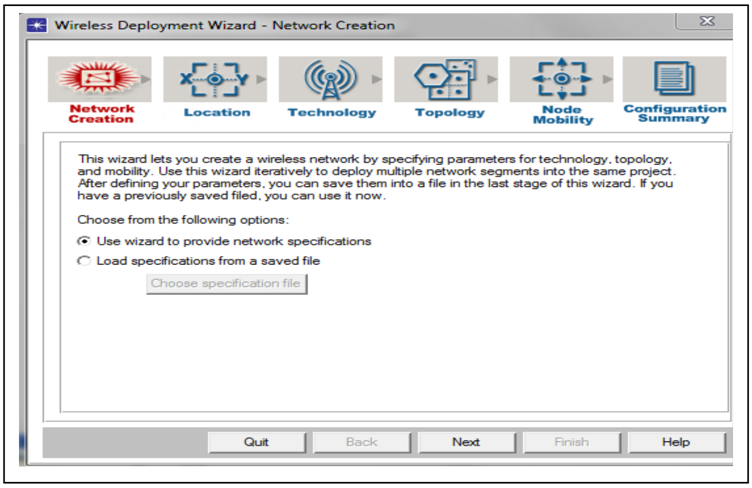

Figure 4.5: Network Creation

Network Creation:

- configure a new network segment with the help of the wizard.
- load specifications from a saved file, if user wants to use a file that have been saved from a previous run of the wizard.

Location:

- define location specifications in terms of X and Y coordinates.

Technology:

- Select the wireless technology that you want to deploy in the network for example WLAN, WIMAX, TDMA, LTE.

Topology:

- Specify a geographical overlay for the wireless subnet which can be selected from the drop down menu such as the area in square meters and number of cells and the cell radius in kilometers.

Node Mobility:

- Specify the node models with which to populate the network segment and specify node mobility parameters for the wireless network segment.

Configuration Summary:

- Reviews and shows the specifications entered and to save the file.

For each wireless network creation, there are other main important settings applied, which are the Application Definition and Profile Definition as shown in Figure 4.6 and Figure 4.7 respectively.

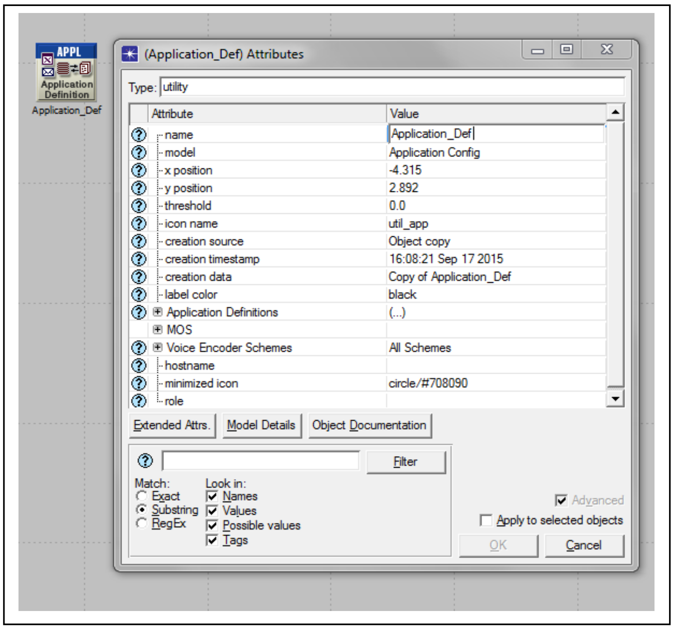

Figure 4.6 : Application Definition

The Application Definition Attributes is to specify applications using available application types. User can specify a name and the corresponding description in the process of creating new applications. The specified application name will be used while creating user profiles on the Profile Configuration object. In addition, another attribute that needs to be set is the Voice Encoder Schemes, which is used to specify encoder parameters for each of the encoder schemes used for generating voice traffic in the network [131].

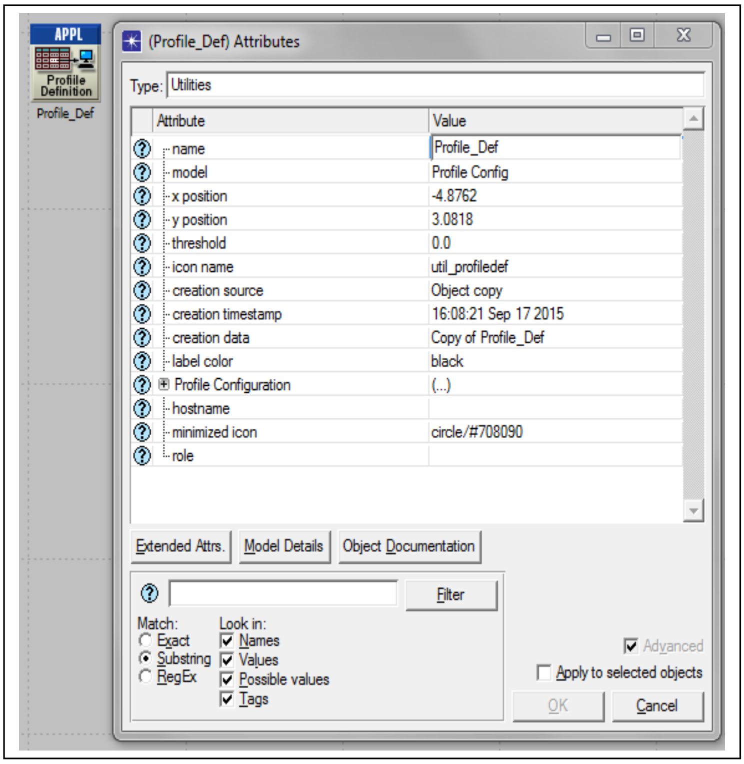

Figure 4.7: Profile Definition

The Profile Definition object can be used to create user profiles. These user profiles can then be specified on different nodes in the netwok to generate application layer traffic. The applications defined in the Application Definition objects are used by this object to configure profiles. Therefore, user must create applications using the Application Definition object before using this object [131].

4.2.2 The WiMAX Module

The WiMAX model used in this thesis is based on the WiMAX module developed in Opnet Modeler. The main objects needed in the WiMAX module are the WiMAX Configuration Object, WiMAX base station and WiMAX sub stations. Details about WiMAX Configuration Object settings can be seen in Figure 4.8.

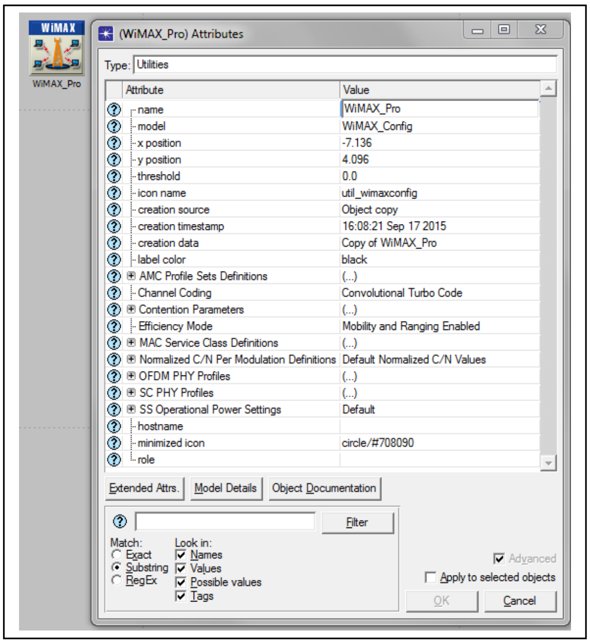

Figure 4.8 : WiMAX Configuration Object

The WiMAX Configuration Object is used to store profiles of PHY and Service Class which can be referenced by all WiMAX nodes in the network. Basic explanation for each parameter settings are [132]:

PHY Parameters:

- Characterizes an OFDM type of profile.

- The frame structure to be used in the network.
- Specifies the duplexing method with only TDD currently supported in the model.
- The frequency band in which the OFDMA channel functions.

MAC Parameters:

- This attribute allows configuration of parameters that make up a service class. A service class groups the QoS requirements of a service flow. Any service class definition can be referenced by any other service flow (uplink/downlink) defined in the network.
- Specifies the service class name based on the service flow.
- The scheduling type specifically to the bandwidth request or grant mechanism for any connection of this class.
- Maximum Sustained Traffic Rate which defines the peak rate for the traffic coming from the higher layer to the 802.16 MAC.
- Minimum Reserved Traffic Rate which specifies the minimum guaranteed data rate for a given service flow of this class.
- Maximum Latency that represents the time elapsed between two consecutive allocations. Currently, this attributes only takes effect for UGS and ertPS connections.
- Unsolicited Poll Interval which specifies the duration between two consecutive unsolicited pools granted to all connections sharing this service slot. A poll is an opportunity for sending a bandwidth request from the SS towards the BS, on behalf of a given connection.

Efficiency Mode:

- This is to schedule grants for the transmission as bandwidth requests come in and as there is availability with respect to the finite data capacity of the PHY. The attribute setting takes effect over the whole network model. There are four options for this: Efficiency Enabled, Framing Module Enabled, Physical Layer Enabled, and Mobility and Ranging Enabled.
- Efficiency Enabled: produces comparatively fewer events, this reduces simulation time and enhancing the scalability of a WiMAX simulation. This is done at the expense of some accuracy, however, the extra accuracy is not typically needed in cases such as network planning.
- Framing Module Enabled: the simulation does a frame-by-frame modeling of allocations on the UL and DL. However, still no physical layer effects are modeled.
- Physical Layer Enabled: the simulation accounts for physical effects and frame-by-frame modelling is also performed.
- Mobility and Ranging Enabled: the simulation accounts for mobility and ranging effects. Physical layer effects and frame-by-frame modelling are also performed.

AMC Profile Sets:

- Defines the profile sets that can be used by the Base station on the UL and the DL for Adaptive Modulation and Coding.

Configuration for WiMAX Base Station settings are as follow:

- PHY profiles: PHY profiles are grouped into two main classes: Single Carrier (SC, SC-a) and Orthogonal Frequency Division Multiplexing (OFDM, OFDMA). A BS node and its associated SS nodes should be configured with the same PHY profile type and is to be used for all communications from/to this MAC.
- Maximum Transmission Power: the power specified in this attribute refers to the total transmission power that this transmitter can output over the entire channel bandwidth. On a Base Station, the total transmission power is fixed and is set as specified by user. On a Subscriber Station, if the efficiency mode is set to Mobility and Ranging Enabled, the total transmission power can be changed dynamically as commanded by the ranging module. For all other values of the efficiency mode, the total transmission power is fixed and is set as specified by the user.
- MAC Address: This attribute specifies address of the WiMAX MAC. This should be a unique value among all types of MAC (example ethernet, WLAN, etc) in the network. By default, the simulation will assign unique values to all MAC modules. In addition, a user can specify an address. If duplicate addresses are detected, simulation will be stopped.
- Classifier Definitions: allows mapping of higher layer traffic to a WiMAX service class. Each map consists of a match criteria and corresponding service class.
- BS Parameters: to set the capability of a BS in UL and DL.
- Antenna Gain (dBi): used to bypass the antenna gain computations at this node and use a provided gain value for all directions.

Configuration for WiMAX Sub Station settings are as follow:

- Application Supported Profiles: specifies the names of all profiles which are enabled on this node. Each profile is defined in detail in the profile configuration object that can be found in the utilities palette. A profile describes user behavior in terms of what applications are being used and the amount of traffic each application generates.
- Application Supported Services: parameters to start and setup services for various applications at this server. Clients can send traffic to this server for only those applications which are supported by this attribute.
- Antenna Gain: This attribute can be used to bypass the antenna gain computations at this node and use a provided gain value for all directions.
- Classifier Definitions: to allow mapping of higher layer traffic to a WiMAX service class. Each map consists of a match criteria and corresponding service class.
- BS MAC Address: This attribute is used by an SS MAC to identify its serving BS MAC. For Auto Assigned settings, an SS node will use the MAC address of the BS node with the maximum received power. This attribute replaces the BS discovery procedure achieved during network entry of an SS node. Once the BS is identified by this attribute, it will be used by the SS for the entire simulation duration.
- Downlink Service Flows: This attribute specifies the properties of the downlink service flows. These flows originate at the BS and terminate at this SS node. Several downlink service flows may be configured. There should be only one downlink service flow to this node with a given service class name.
- Uplink Service Flows: This attribute specifies the properties of the uplink service flows. These flows originate at the SS and terminate at the BS node. Several uplink service flows may be configured. There should be only one uplink service flow from this node with a given service class name.

- Control Connections: This attribute specifies the properties of the control connections. Currently only Basic connection is defined. The configuration is applied to both uplink and downlink instances of the connection.
- Multipath Channel Model: The channel model is defined on the SS and it applies to the channel between the SS transmitter and the BS receiver, as well as the channel between the BS transmitter and the SS receiver. In other words, the channel model specified on an SS applies to both the uplink and the downlink transmissions involving that SS. When the SS moves from one cell to another, it carries the channel model with it into the new cell.
- Pathloss Model: This attribute specifies the type of pathloss model to be applied to signals being received at this WiMAX MAC. Each pathloss model is appropriate for a certain kind of environment through which the signal propagates before reaching the receiver. The Free Space pathloss model refers to the classical free space pathloss. The "Suburban Fixed (Erceg)" pathloss model is defined in: V. Erceg et al., as "An empirically based path loss model for wireless channels in suburban environments", IEEE JSAC, vol.17, no.7, July 1999, pp. 1205-1222. Erceg's model is also referenced in IEEE802.16a-03/01 document. The "Outdoor to Indoor and Pedestrian Environment" and the "Vehicular Environment" are pathloss models described in the "Radio Tx Technologies for IMT2000" white paper of the ITU.

4.2.3 The WLAN Module

The model of WLAN in Opnet is built to demonstrate some of the implemented features and algorithms of the WLAN technology, specified in IEEE's 802.11, 802.11a, 802.11b, 802.11g, 802.11e, and 802.11n standards [133].

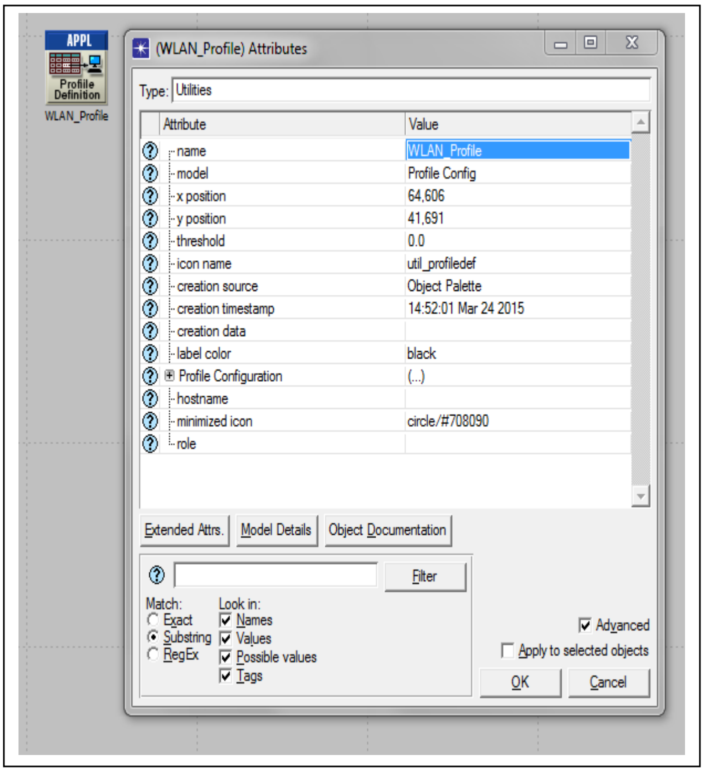

Figure 4.9: WLAN Configuration Object

The WLAN Configuration Object (see figure 4.9) is used to store profiles for each of WLAN application profiles. Basic explanation for each parameter settings are [134]:

- Profile Configuration: A profile describes user activity over a period of time. A profile consists of many different applications. The profiles created on this object will be referenced by the individual workstations to generate traffic.
- Application: Each application is described in detail within the application configuration object.
- Profile Name: Name of the application configured in this profile.

- Start Time Offset: This attribute has two interpretations based on the value specified for the Operation Mode.
- Operation Mode: If the Operation Mode is set to Simultaneous, this offset refers to the offset of the first instance of each application (defined in the profile), from the start of the profile. If the Operation Mode is set to Serial (Ordered) or Serial (Random), this offset refers to the time from the start of the profile to the start of the first application. It also serves as the inter-application time between the end of one application to the start of the next. If an application does not end (duration set to End of Profile), subsequent applications will not start.
- Duration: The maximum amount of time allowed for an application session before it aborts. This is often used as a timeout. When it is set to End of Profile, the application will end when the profile duration has expired. When it is set to End of Last Task, the application will end when the last task of the application has completed regardless of task completion times.
- Repeatability: Specifies the parameters used to repeat applications within the surrounding profile.

Configuration for WLAN Sub Station settings are as follow:

- Application Supported Profiles: A profile describes user behavior in terms of what applications are being used and the amount of traffic each application generates. Profiles can be repeated based on a repeatability pattern.
- Application Destination Preferences: Provides mappings between symbolic destination names specified in the Application Definition.

- Application Supported Services: Parameters to start and setup services for various applications at this server. Clients can send traffic to this server for only those applications which are supported by this attribute.

4.3 WiFi/WiMAX Model

To allow the interoperability between WiFi and WiMAX as a hybrid network, a special gateway is needed known as WiFi/WiMAX gateway [135]. The main use of this gateway is to connect the users of both technologies seamlessly with greater gain access as shown in Figure 4.10.

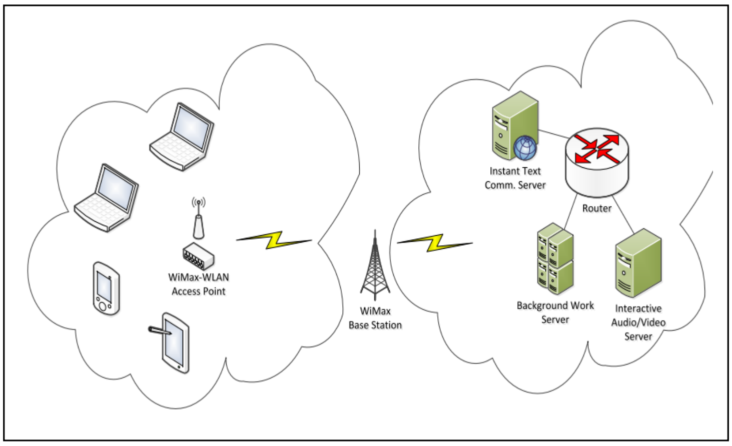

Figure. 4.10: WiFi-WiMAX coexistence topology [136]

For this type of combination, the WiFi users connect to the Internet through a WiMAX core network using the WiFi/WiMAX gateway [137]. The WiMAX base station sees the gateway as another WiMAX subscriber station. Therefore in this section, a description about the WiFi/WiMAX Router or named as CPE will be discussed.

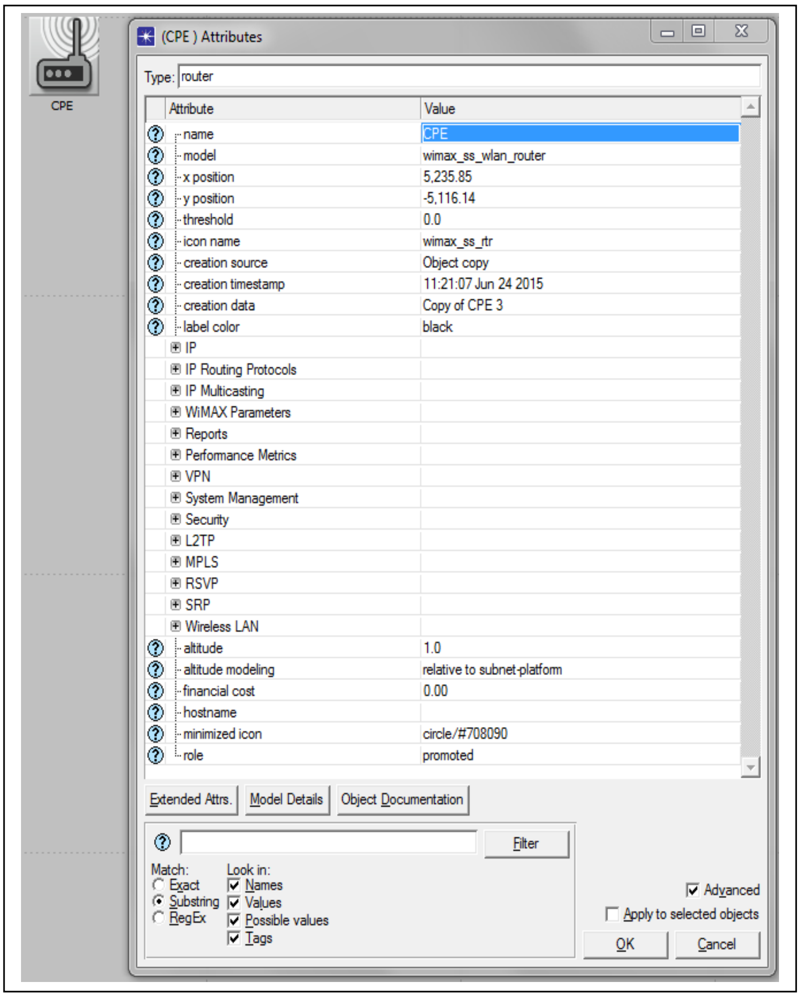

Figure 4.11: WiFi/WiMAX Router

Figure 4.11 shows the WiFi/WiMAX Router configuration in Opnet. Basic explanation for each parameter settings are [128]:

WiMAX Parameters:

- Antenna Gain (dBi) : This attribute can be used to bypass the antenna gain computations at this node and use a provided gain value for all directions.
- Classifier Definitions: This attribute allows mapping of higher layer traffic to a WiMAX service class. Each map consists of a match criteria and corresponding service class.
- Traffic Characteristics: This attribute specifies the match criteria for mapping higher layer traffic to WiMAX service flows.
- Service Class Name: This attribute specifies the name of a service class for the traffic matching the defined characteristics. This service class name is later used to find a service flow.
- PHY Profile: This attribute specifies the PHY profile to be used for all communications from/to this MAC. A BS node and its associated SS nodes should be configured with the same PHY profile.
- SS Parameters: Subscriber station parameters - definitions of service flows, ranging parameters, mobility parameters, AMC parameters, piggyback bandwidth request support, power control, power saving parameters.

WLAN Parameters:

- MAC Address: Specifies the WLAN layer's unique MAC address.
- BSS Identifier: This attribute identifies the BSS to which the WLAN MAC belongs. In case of Auto Assigned, all WLAN MACs in each subnet belong to the same BSS (the subnets define the borders of the BSSs in the network). If this attribute is used (set to a value different than Auto Assigned), then it should be configured globally for all the WLAN nodes or interfaces in the network. For WLAN MACs, whose roaming

functionality is enabled, this attribute identifies only their initial BSSs. They may associate with other BSSs later during the simulation.

- Access Point Functionality: Can be used to assign the MAC as the access point of its BSS and to enable the access point functionality in the MAC by setting its value to Enabled.
- PHY Characteristics: Based on the value of this attribute, which determines the physical layer technology in use, the WLAN MAC will configure the values of the following protocols parameters as indicated in the IEEE 802.11 WLAN standard.
- Data Rate (bps): Specifies the data rate that will be used by the MAC for the transmission of the data frames via physical layer. The set of supported data rates depending on the deployed physical layer technology are specified in IEEE's 802.11, 802.11a, 802.11b, 802.11g and 802.11n standards.
- Channel Settings: Specifies the frequency band that will be used by the radio transmitter and receiver connected to the MAC. The channel numbers correspond to the channels available in the 2.4 GHz ISM band (specified in IEEE 802.11, 802.11b and 802.11g), and 5 GHz U-NII band (specified in 802.11a).
- Transmit Power: Specifies the transmit power of the STA in Watts. Note that no limits are imposed upon the value of this attribute.
- Packet Reception-Power Threshold: Defines the received power threshold (receiver sensitivity) value of the radio receiver in dBm for arriving WLAN packets. Packets with a power less than the threshold are not sensed and decoded by the receiver.
- Buffer Size: Specifies the maximum size of the higher layer data buffer in bits. Once the buffer limit is reached, the data packets arrived from higher layer will be discarded until some packets are removed from the buffer so that the buffer has some free space to store these new packets.

4.4 Evaluation of the WiMAX System Simulation

Simulations for several scenarios were conducted to verify the WiMAX module using Opnet. This segment begins with depiction and cases where WiMAX was used in an emergency situation especially in a real time situation. Next the explanation on the scenario used in the simulation, followed by the simulation results and the examination. Finally, the outcome of the WiMAX QoS behavior is outlined and discussed.

In this research, the reasons why we chose WiMAX as the solution was due to several reasons; WiMAX network can be deployed in the risk and inaccessible areas for example in a place where the disaster happened (earthquake, seaquake, flooding, and forest fires) and even in the proximity of a possible hazard such as volcanoes and nuclear power stations [3]. The selection of WiMAX based communication architecture is the best solution due to its capabilities in terms of coverage, data rates, user mobility and even enables meeting different QoS constraints in relation to different types of applications and traffic [4]. In particular, in the case of an emergency communication system, it is possible to allocate network resources properly and to assign priority to critical applications, such as real-time applications.

4.4.1 WiMAX in Disaster Situations

In many practical applications or situations where emergency communication is required, very often the major communication is down. It has also happened during times of catastrophe such as earthquakes or tsunamis, when the entire incumbent communications infrastructure is destroyed or damaged [1]. An ad-hoc communication system that requires relatively fast and robust links must be deployed in a very short time to support the communication needs of the rescue and recovery operations [2]. For example in the 2010 Haitian Earthquake response, VoIP, video and applications such as Skype, Ushahidi, Sahana, Facebook, Twitter, and Google Maps were used by the disaster responders for the emergency communications [138].

There are two scenarios that have been used by the WiMAX Extensions for Remote (WEIRD) and Isolated Research Data Networks project; Environmental Monitoring and Fire Prevention [139]. For the environmental operation, several video cameras and wireless sensor networks were installed around the area to record any occurrences that happened. Next, all the data was collected and transmitted to the Monitoring Centre using a Mobile WiMAX link to be analyzed [140]. The same procedure goes for the Fire Prevention Scenario, images and text descriptions taken from the operation site were being transmitted to the Fire Station District Civil Protection Coordination Centre (DCPCC) using Mobile WiMAX. For this case, real-time data such as voice and VoIP application have been used and utilized [138].

Next, the evaluation of WiMAX as a homogenous system is conducted, particularly in disaster situations. Two scenarios are presented here to evaluate the performance; Scenario 1 and Scenario 2.

4.4.2 Scenario 1

In this scenario, we analyzed the performance of the rtPS and BE QoS. Currently in WiMAX there are 5 different QoS and it is commonly known that rtPS provides higher quality and BE provides the worst quality. However, in the case of a disaster, there is a need to have any type of communication. It is also desirable to get more from the system performance what the conventional system can do. One of the conventional thinking is that rtpS QoS will always give the best performance with the higher throughput while BE QoS is like a backup [141]. Therefore, we wanted to investigate whether BE QoS could perform better than the rtPS in terms of throughput, delay and packet loss.

4.4.3 Simulations

The model consists of 1 BS and 10 SS and is simulated using the Opnet simulator. rtPs and BE are involved in evaluation with the following traffic combinations: 8 video conferencing connections and 2 http browsing. The video conferencing traffic is given the rtPS treatment whereas the http browsing is specified to be BE scheduling type. The service flows for both classes are classified as Silver. The traffic parameters and simulation parameters are summarized in Table 4.1 and 4.2 respectively.

Table 4.1: Traffic Parameters

Application	**Parameters**
Video Conference	Frame size :128x120 resolution Frame inter arrival time : 10 fps
Web browsing (HTTP)	HTTP Specification : HTTP 1.1 Inter arrival time :Exponential 360 seconds

Table 4.2: Simulation Parameters

Parameter	**Value**
PHY Profile	OFDMA
Bandwidth	10 MHz
No. of Subcarriers	1024
TTG (Transmit-receive Transition Gap)	106 µs
RTG (Received-transmit Transition Gap)	60 µs
Min Reserved Traffic Rate (rtPS)	140 kbps
Max Sustained Reserve Traffic Rate	2.8 Mbps
Poll interval rtPS	5 ms
Subframe ratio (DL/UL)	1:1

4.4.4 Results and Discussion

The simulation has been carried out to compare the performance of the rtPS and BE QoS in WiMAX network. Figure 4.12, Figure 4.13 and Figure 4.14 demonstrates the situation where BE QoS could perform better than rtPS QoS users in a WiMAX network.

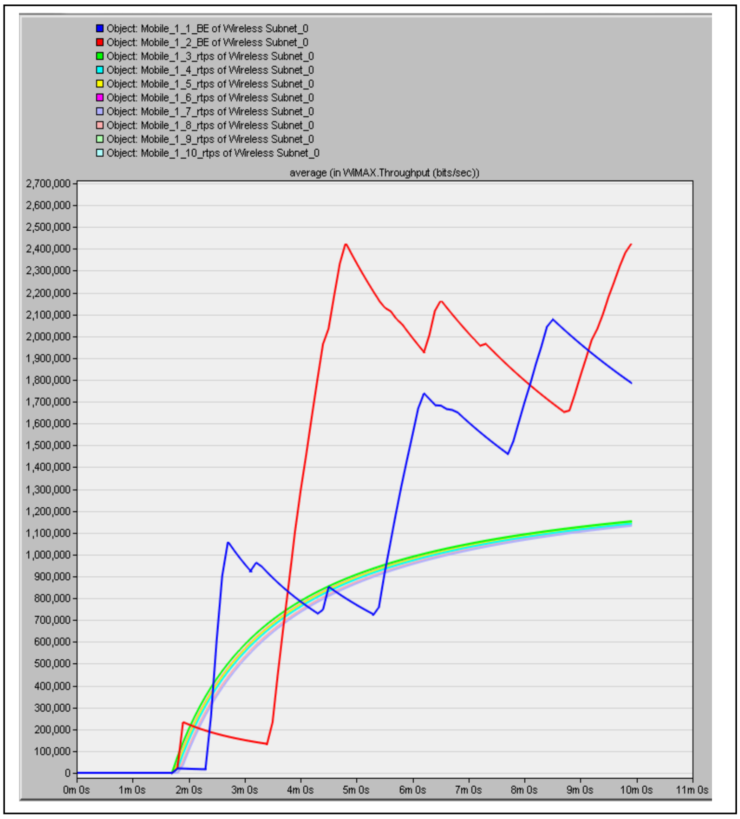

Figure 4.12: Average throughput for rtPS and BE

Figure 4.12 shows the average throughput for rtPS and BE QoS users. Herein, the average throughput is defined as the average data rate achievable for all the users in the scenario. For both BE QoS, the average throughput is around 2.4 Mbps and 2.1 Mbps respectively. However, for remaining 8 rtPS QoS users, the average throughputs are ranged between 1.1 Mbps to 1.2 Mbps. It clearly shows that the BE users have higher throughput than the rtPS [27] .

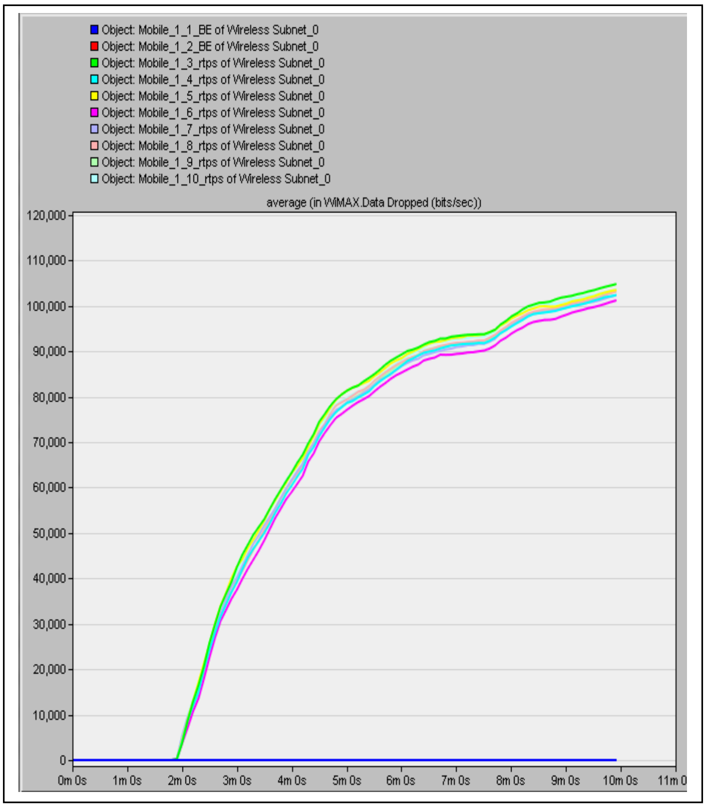

Figure 4.13: Average data dropped for rtPS and BE

This scenario can be further investigated from Figure 4.13, where we can observe that, for both BE users, there is no packet drops between the BS and SS link. Meaning, there is no data loss from the source to the destination that will likely degrade the file transmission.

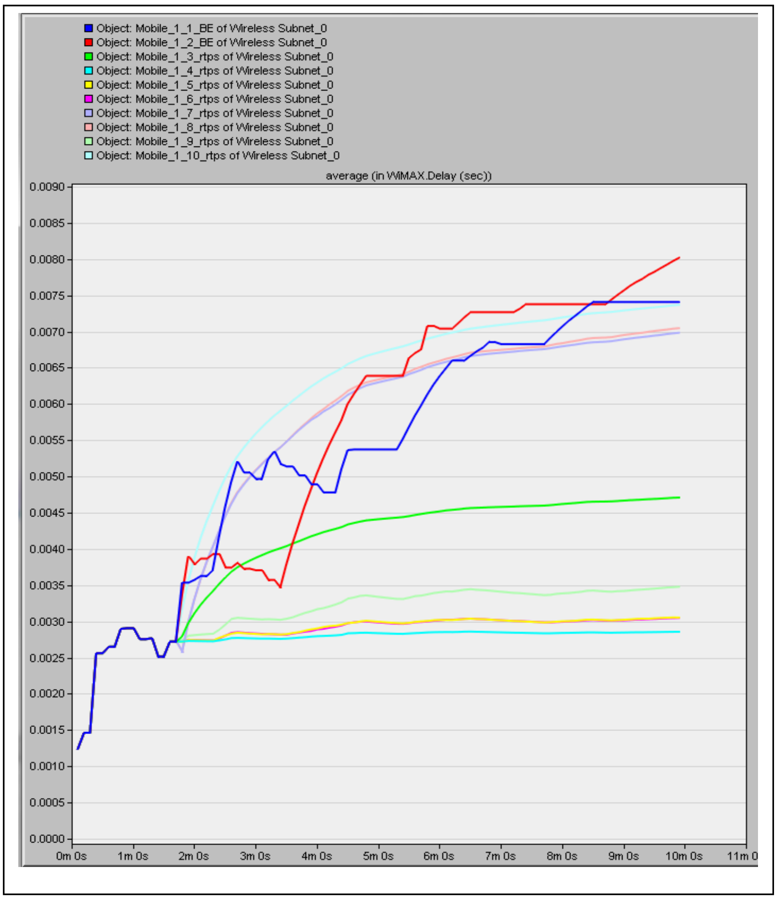

Figure 4.14: Average delay for rtPS and BE

The delay measured for the video conferencing and http application is detailed in Fig.4.14. It is shown that the average delay ranges from 0.008 to 0.0035 seconds for the BE users. The average amount for the rtPS users ranges from 0.007 to 0.003 seconds, which is smaller than the 150 milliseconds specified by the WiMAX forum as the acceptable delay for video conferencing application.

4.4.5 *Scenario 2*

Another concern is the application assigned for each WiMAX QoS which is evaluated in Scenario 2. Conventional WiMAX standard defines 5 levels of quality of service and in this level video conferencing/streaming is assigned to the rtPS classes [142]. However, there are a number of scenarios where video conferencing can work with the BE QoS for example, in the WiFi network [143]. We anticipated that such scenarios will happen in emergency situations, therefore we would like to try these unusual scenarios where video conferencing could be required to operate with the BE. Eventhough video conferencing is not used over BE classes but let's assume for this particular case the user does not have any other choice. So our systems solution is to provide this user with enough throughput so that the user can run video conferencing/streaming application over BE QoS class, which is not commonly possible. We also proposed not only video streaming for rtPS QoS user, but also web browsing for the rtPS user. The following figures are the results from evaluating the BE QoS with the video conferencing applications. Eventhough it is an unusual case, based on this discovery, it can be very useful to the rescue team during disaster or an emergency situation.

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4.4.6 *Simulations*

The next model contains 10 users with the specific QoS allocation as depicted in Table 4.3.

Table 4.3: WiMAX User Allocation

WiMAX QoS	Number of WiMAX User	Application Assigned
rtPS	3	web browsing
BE	2	video conferencing/streaming
rtPS	5	video conferencing/streaming

Figure 4.15 depicts that the average throughput for the 3 rtPS (web browsing) users ranges between 650 kbps and 1.05 Mbps. Meanwhile, for the 2 BE and 5 rtPS (video conferencing/streaming) applications, the throughput was 1.15Mbps, respectively. Therefore it shows that BE QoS could also function with the video conferencing applications and eventually perform slightly higher throughput compared to the rtPS (web browsing) application.

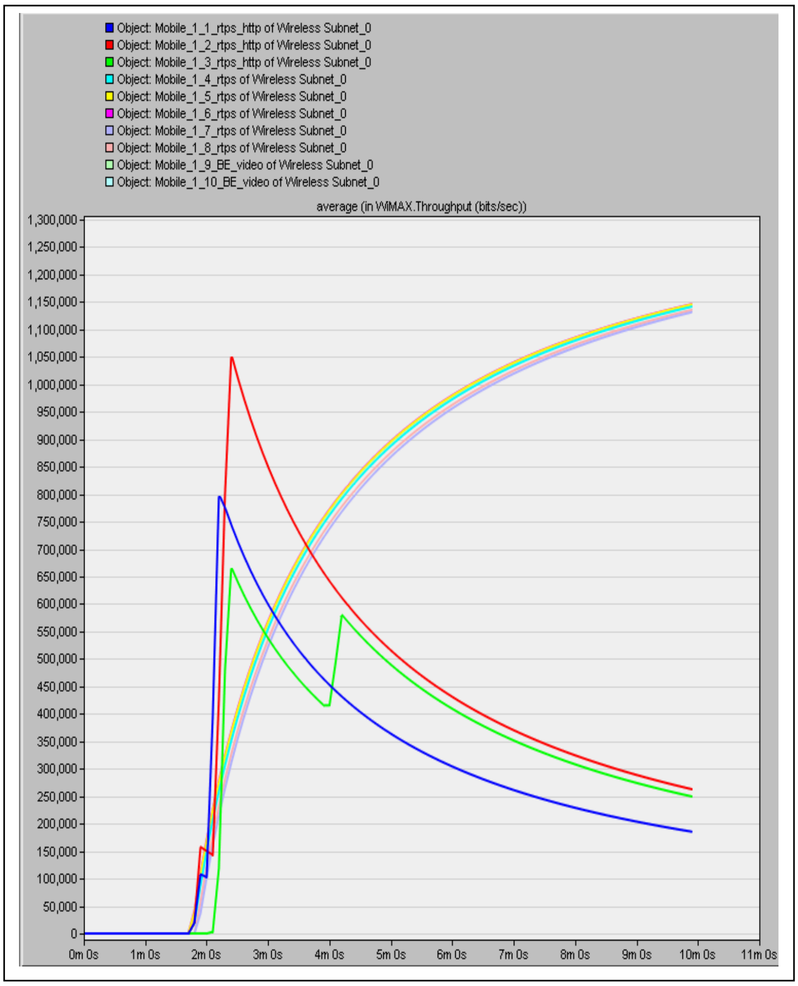

Figure 4.15. Average throughput for rtPS and BE

In Figure 4.16, delays of video conferencing applications with BE connections seem to be significantly lower compared to those with rtPS connections as indicated in Figure 4.17. Owing to the stringent delay requirements for video communication applications, the scheduler must ensure that the services reach their destinations on time.

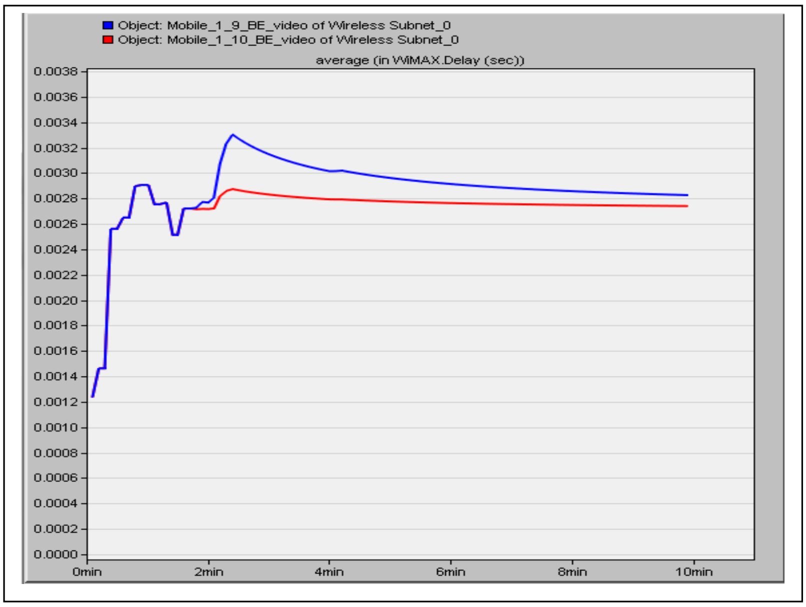

Figure 4.16. Average delay for BE users

On the contrary, the delays posed by the data transfer applications in Figure 4.17 are slightly higher even with rtPS connections. This is because the data transfer applications are not bound to any delay requirement. However, the delays for both BE and rtPS connections are still lower than the targeted delay requirement [144].

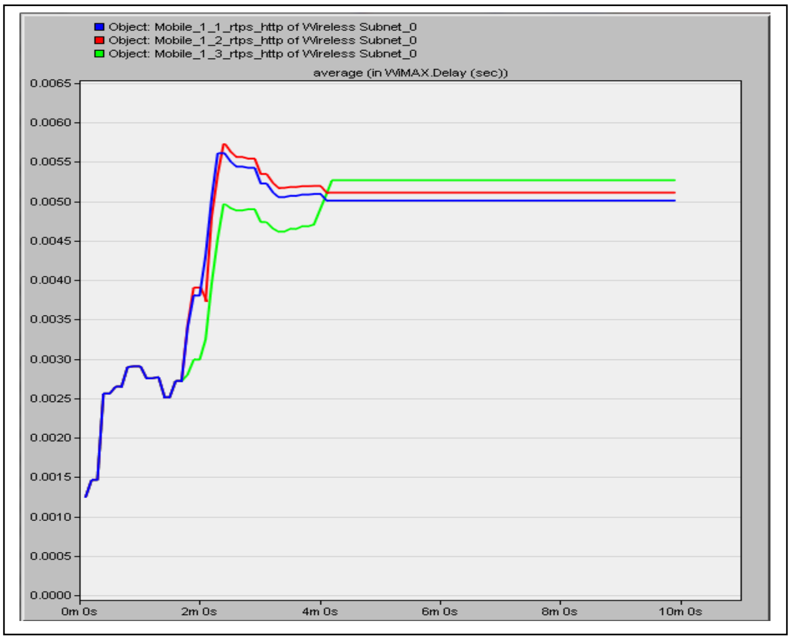

Figure 4.17. Average delay for rtPS users

4.5 Summary

In this section, we presented an overview of the parameters settings for WiMAX and WLAN modules in Opnet. Also, we evaluated the WiMAX module which will be used in our next project that will be explained in the next chapter. We investigated QoS performance in WiMAX module focusing on the rtPS and BE scheduling classes. Based on the results obtained, it can be concluded that in some specific scenarios, it is possible to get a better throughput with BE rather than rtPS. We proposed this novelty to the emergency rescue services as this could be a very good addition to those who would need extra bandwidth without the need to deploy extra base stations. In fact, in some disaster scenarios, the particular environment can limit the number of base stations in the area and hence, higher throughput could satisfy the main requirement.

Besides that, we evaluated the cross layer approach whereby we assigned the real time applications to the non-guaranteed bit rate classes and vice versa. We found that BE classes is also probably suitable for the video conferencing applications which could possibly be used during an emergency situation.

Chapter 5: Optimization for Integration of WiFi and WiMAX Network for PPDR Services (Major Planned Event)

Public Protection and Disaster Relief (PPDR) is the most important organization that is responsible for the disaster preparedness and recovery [84]. In times of catastrophe such as earthquakes or tsunamis, particularly when the major incumbent communications infrastructure was destroyed or damaged, a relatively tight and robust communications system needs to be deployed in order to support the communication needs of the search and rescue operations. Therefore, PPDR organization will assist the emergency communications among the first responders on the site including firefighters, emergency response personnel, law enforcement and also disparate agencies.

I was involved in the European Union (EU) project organized by the PPDR Transformation Center (TC). PPDR-TC is a project that involves several partners of different nature and expertise and requires a careful planning as well as procedures to achieve its necessarily ambitious objectives. PPDR-TC has launched a project with the title of Public Protection and Disaster Relief-Transformation Center, Call Identifier: FP7-SEC-2012.5.2-1. The main objectives of the project is preparation of the next generation of PPDR communication network. Therefore, my task was to prepare the simulation results based on the given scenarios. The layout needed for each scenario, based on PPDR requirements, were prepared by the engineers from Rinicom LTD. Besides that, I was also given the role to investigate and propose the best/optimum results, which in the future, will be used as an EU standard and by the first responders in any emergency case. Thus, in Chapters 5 and 6, the discussion involves integration of WiFi and WiMAX, mainly focusing on the PPDR users.

However, this chapter will concentrate on the Major Planned Event situation, whereas the Unplanned Event will be discussed in the next chapter.

5.1 Introduction

In a large international disaster scenario, there are multiplicity of different PPDR organizations that may be involved to support the mission. Nevertheless, they may use different wireless communication technologies, which create interoperability barriers [145]. In this chapter, I proposed a hybrid communication architecture that involves the integration of WiFi and WiMAX using a special router known as WiFi/WiMAX router, for the operation of emergency situations. Previously, PPDR organizations have used voice services to perform their operational duties. Nevertheless, non-voice communications is becoming equally important [87] to diverse applications such as video streaming, picture download, and remote database depending on the nature of the tragedy. A complete list of current and future applications needed for PPDR services are described in [146], which explains the necessity of data connectivity in their operations. In this thesis, we also proposed an optimize combination number of applications that can be maintained in the integration of WiFi-WiMAX network.

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5.2 PPDR-TC

Public Protection and Disaster Relief-Transformation Center (PPDR-TC) was a project that had the involvement of several partners of different nature and expertise that were directly involved in PPDR operations. The main objective of the project was to increase the efficiency of communications infrastructure by the enhancement of new communication technologies in order to achieve interoperable, secure and resilient communication - tailored specifically for the future needs of the PPDR community. Following this, the integration and participation of end-users, with specific knowledge in public safety issues, play a key role in

Commented [ez8]: Or from different fields the development of PPDRs, while making the project's goals more concrete. Details objectives of the PPDR-TC are explained in Table 5.2.

Table 5.1: PPDR-TC Objectives [147]

Objective	**Details**
1	To gather European PPDR facts and figures data.
2	To define PPDR reference usage scenarios and identify service requirements and future needs in the European context.
3	To implement a detailed study of the reference scenarios with a view to establishing service classification and identifying key technical issues.
4	To identify candidate PPDR technologies and architectures.
5	To identify and customize validation tools for future PPDR.
6	To derive technical recommendations on candidate technologies and architectures.
7	To provide economical recommendations on candidate technologies and architectures.
8	To provide a roadmap towards full satisfaction of future PPDR requirements and to develop recommendations for PPDR standards for decisions-makers

In relation to my research, my main task was to build a hybrid model that can be applied to the PPDR operations. Therefore, I developed a hybrid wireless broadband network, which is a WiFi+WiMAX hybrid model with guaranteed QoS. Ihad also prepared the simulation results using the WiFi+WiMAX hybrid system and analysis of the outcomes with the expertise from industry for the validation process. In addition, I proposed several new findings or results that would benefit the PPDR projects. All these were not carried with other partners or consortium involves in the PPDR-TC.

5.3 Integration of WiFi and WiMAX in Disaster Situation

This section discusses the mechanism of the integration of WiFi and WiMAX starting with a general view of each protocol in each system particularly for disaster or emergency situation.

Every bit a beginning version of wireless solution, the WiFi is considered as the very high-speed WLAN mechanism to plug in laptops, cell phones and other appliances. Curently, WiFi is popularly employed in Internet access, VoIP communication and many more with a speed of 54 Mbps and a reach of approximately 30 meters [9]. On the other hand, WiMAX is high-speed WMAN wireless technologies of recent days. It is a standard that was built with the intention to supply long distance wireless connectivity with a theoretical data rate of 70 Mbps with a range 50 km. Nevertheless, the achievable data rate with current version is 10 Mbps at a reach of 2 kilometers [10].

Although, both the technologies of the WiMAX and the WiFi provide a wireless connection to last mile problem, their working mechanism is technically different [11]. One of the primary reasons why WiFi is unable to work at greater distances as WiMAX is that radios operating in the unlicensed frequencies are not admitted to be equally potent as those operated with licenses [12]. Since the power is less, the same effects happen to the distance. Secondly, the WiFi MAC layer uses contention access, whereas WiMAX uses a scheduling algorithm. Using a contention mode algorithm, users have to compete for data throughput to the access level. In the interim, by scheduling mode algorithm, it lets the user to only compete once on the access level. As a result, WiMAX outstrip WiFi in terms of throughput, latency, and spectral efficiency [13].

Despite such high data rate and long distance coverage, WiMAX is not widely used as WiFi. The primary reason is the price involved in WiMAX deployment, which is related to the licensed frequency band used in WiMAX standard. The frequency band used in WiFi is ISM band, hence, the cost involved in fixing up the WiFi network [14] is rather high. Thus, to minimize the cost of setting up a wirelessly connected network with quality of service, researchers are attempting to integrate both WiFi and WiMAX into a single operating environment.

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Both WiFi and WiMAX standards are designed for the Internet protocol applications. However, by combining these two technologies, WiMAX can function as a backhaul while WiFi will be connected directly to the users [15]. During times of catastrophe such as earthquakes or tsunamis, when the entire incumbent communications infrastructure was destroyed or damaged, an ad-hoc communications system that requires relatively fast and robust links must be deployed in a very short time to support the communication needs of the rescue and recovery operations. Therefore, using this type of WiFi and WiMAX integration network, communication needs among the first responders, the victims and headquarters can be deployed. After an emergency call has been received, vehicles and personnel belonging to several authorities are sent to the incident scene. Rescuers have to immediately seek for people who require quick assistance. At the same time, they have to set up communications for various tasks such as, transmission of live video event from a disaster area to the fire department's command center, data transmitting to the corresponding headquarter, medical data fetching from hospitals' databases regarding the medical chronicle of the injured persons and, also when the people involved are trying to communicate with their relatives. This situation is even vital when the main communication infrastructure is totally unavailable [83].

Nevertheless, due to WiFi coverage is restricted to approximately 200m, such a coverage is not passable for emergency operations as disaster areas can span up to several hundreds of meters or kilometers. Compared to WiMAX coverage, which is up to 50km with a 70 Mbps data rate, it seems that WiMAX is the best option to be habituated. Furthermore, on that point are certain drawbacks about WiMAX technology as presented in Table 5.4. It also sums up the restrictions and benefits of the current technologies for use in emergency response mission critical communications.

Table 5.2: Limitation/shortcomings and benefits of current technologies for emergency response communications [83]

Technology	**Limitations/shortcomings**	**Benefits**
Cellular	Low to medium bandwidth, centralized architecture, high cost of infrastructure deployment and maintenance	High mobility, high coverage, high penetration of smart phones, broadcasting mechanism for audio and video transmission
Satellite	Asymmetrical transmission rates, high cost of equipment, heavy weight of equipment	Immune to terrestrial congestion, coverage in even sparsely populated areas, high transmission rates
TETRA	Centralized architecture, low transmission rates	A good established and mature technology, expansion to many countries
WiFi	Limited coverage, intra and inter-channel interference	High transmission rates, use of unlicensed spectrum, rapid proliferation of WiFi enabled devices
WiMAX	Centralized architecture, licensed spectrum use, high cost of infrastructure deployment and maintenance	High transmission rates, proliferation of WiMAX enabled (smart phones, femtocells)

5.4 EU Project Summaries

There are two operational scenarios considered in this project; Major Planned Event and Unplanned Event. The Major Planned Event network is modeled with WiMAX as backhaul to the core IP network, whereas in the Unplanned Event, each WiMAX BS is connected to a PPDR centre. The next section provides the summary of the results from the EU project report for both scenarios.

5.4.1 WiFi – WiMAX (backhaul) Major Planned Event

This simulation presents the results for a WiFi network using WiMAX as backhaul to the core IP network. Each WiMAX base station is linked to a WiMAX CPE (AP device which has built-in WiFi and WiMAX bridge). PPDR users are simulated within range of this WiFi device and are represented as WiFi terminals and all traffic is then transmitted over the WiMAX CPE back to the linked base station and then the core network.

5.4.2 Application modelling

Within this simulation there are several applications which are run as described herein. The applications simulated are shown below and are based on user requirements at the scene of a major event or incident. Results are presented in this report for background traffic levels of 0%, 10% & 50% as the most representative based on the results achieved. The performance effects of additional background traffic and number of network users were shown to be well demonstrated in these 3 different traffic levels and thus further simulations were not necessary, such results would have taken considerable time to run but offered little additional information. OPNET was used as the simulator of choice for these simulations.

Table 5.3: Users breakdown traffic

Users/nodes	Traffic type/application	Technical data
10%	Video	See below
40%	Reliable, burst (web)	See below
70%	Audio (VoIP)	See below
0, 10, 50%	Reliable, continuous background (FTP)	See below

From the table above the breakdown of traffic is allocated between all users/clients in the simulation. As an illustrative example, in the 200 node scenario the application breakdown per users with 10% background traffic is shown below;

- 20 video only users
- 80 VoIP only users
- 40 Web only users
- 40 VoIP & web users
- 20 VoIP & FTP users

As is clear some users are using a variety of applications and others are limited to VoIP/video as would be representative in a PPDR scenario. The FTP application was chosen to represent background traffic at different levels of users (so 0%, 10% & 50% background traffic are focused on assessing the network performance as the background traffic increases). Such variable traffic could be generated by public users of the system if it was leased to PPDR users and the performance impact this has can be seen in the forthcoming results. Video streaming was represented using the built in OPNET feature for video streaming and generated a standard bit rate of approximately 140kbps. The frame rate was reduced in this particular case and this will be used as an indicator for the expected performance that can be achieved using various other streaming protocols. Video application configuration is demonstrated in the table below.

Table 5.4: Video application configuration

Video Application	
Frame size	10 Kbytes
Frame rate	10 fps
Video codec emulated	H261
Operation Mode	Always ON (Serial ordered))
Minimum bit rate over WiMAX	140kbps
QoS Type	rtPS

VoIP application is one of the crucial traffic types for users and was therefore allocated a high priority Quality of Service (QoS) profile using UGS (Unsolicited Grant Service) which guarantees a constant bit rate (fixed at 96 kbps) with minimal delay which is crucial for voice communications. In this instance the codec use was G.711 for all forthcoming simulations with a fixed bit rate of 64kbps.

Table 5.5: VoIP application configuration

VoIP Application	
Encoding	G.711
Compression delay	0.02s
Decompression delay	0.02s
Operation Mode	Serial Random
Max bit rate over WiMAX	96 kbps
Min bitrate over WiMAX	64 kbps
QoS Type	UGS

The final two applications were to represent random/unpredictable requests for bandwidth in a random/burst manner, for this web browsing was chosen as often webpage requests may be made in this random unpredictable way. FTP is used to represent overall background traffic and is a constant load on the network used by a predefined proportion of the users (0%, 10% and 50%) note that this percentage is the number of users generating FTP traffic and not the capacity of the network being utilised. Background traffic is tweaked per simulation run and the resultant effect on network is observed and assessed against other applications and overall performance.

Table 5.6: Web browsing application configuration

Web browsing application	
HTTP Specification	HTTP 1.1
Object size	Constant 500 Bytes
Operation Mode	Serial Random

Table 5.7: FTP application configuration

FTP Application	
File size	50 kBytes
Inter-Request Time	Exponential 360 seconds
Operation Mode	Always ON

5.4.3 Simulation configuration

Within this section the technical description and configuration of the communications technology is provided. For the planned simulation it is envisaged that the infrastructure would be “fixed” in place with the following equipment :

- WiMAX base station: main infrastructure connected to the internet/core PPDR network through an IP backbone and gateway. This equipment would be deployed on the event site before the event and would remain fixed providing coverage to the immediate area. These are placed within the core event area (~500m x 500m), allowing for simple placement of the WiMAX clients and providing minimal drop in data rates/potential interference. The technical configuration for each WiMAX base station in the simulation is shown in the table below;

Table 5.8: WiMAX Base Station configuration

WiMAX Base Station	
Operating Frequency	2.5 GHz
Bandwidth	10 MHz, 1024 (subcarrier)
Transmitter Power	2 W
Antenna Gain	18 dBi

- WiMAX CPE: This device will be deployed a few hundred meters from the base station around the “stadium” area or central site area. Each device acts as a WiFi AP (Access Point) with a bridged connection to the closest WiMAX base station. In this scenario there are up to 20 users per CPE using WiFi terminals with the traffic generating applications already presented, each terminal could represent any WiFi enabled device. Below the technical configuration used within the simulation platform for a CPE is described;

Table 5.9: WiMAX CPE configuration

WiMAX CPE	
WLAN Standard	HT PHY 5.0GHz (802.11n)
Data rate	6.5Mbps to 60Mbps
Antenna Gain	18 dBi
Modulation	OFDM
Max TX Power	3W

- WiFi Client: Representing the PPDR users these devices are placed within range of the WiMAX CPEs and run each of the applications already described. Each terminal generates the user's traffic requirements and this is routed through the WiMAX CPE→ WiMAX base station and to the core PPDR network centre. The technical configuration used for these WiFi terminals is shown in the table below;

Table 5.10: WiFi Client configuration

WiFi Client	
Standard	
Data rate	6.5Mbps to 60Mbps
Antenna Gain	18 dBi
Modulation	OFDM
Max TX Power	40mW
Buffer size	32 000Bytes

5.4.4 Simulation layout

Herein this section describes the physical layout of the individual components and their placement in the simulation model. For the planned scenario event the core WiFi coverage is aimed at the main incident area as the effective range is limited to a 2m to 60m radius dependent on obstacles and RF interference from other terminals/devices and wireless equipment. Within this scenario the number of users involved in the scenario was altered to take into account the varying load that might occur depending on the situation currently occurring and to determine the additional load that would incurred onto the network. As such several simulations were carried out using a varying number of nodes;

- 50 Nodes with 0%, 10% and 50% background traffic
- 100 Nodes with 0%, 10% and 50% background traffic
- 150 Nodes with 0%, 10% and 50% background traffic
- 200 Nodes with 0%, 10% and 50% background traffic

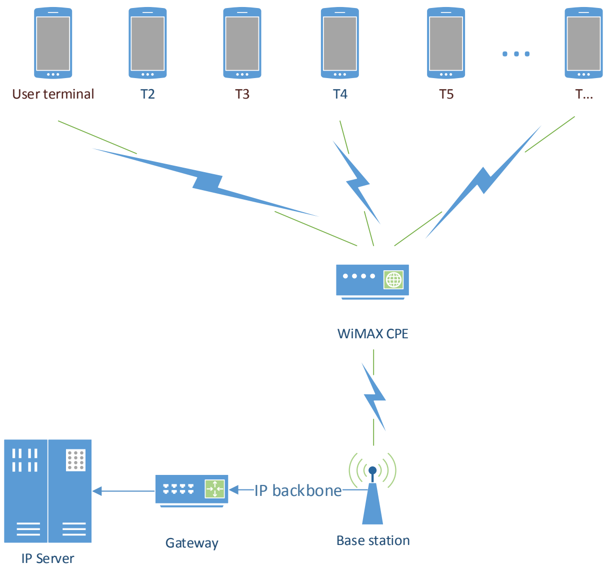

Figure 5.1: Simulation Physical Layout

Network Architecture diagram:

Below is the diagram showing the overall simulation plan for the core incident area (multiple BS (WiMAX base stations) each device is configured as per the figure above and is omitted to reduce the overall complexity of this diagram. Note that the number of users per CPE is dependent upon the number of nodes / PPDR users simulated.

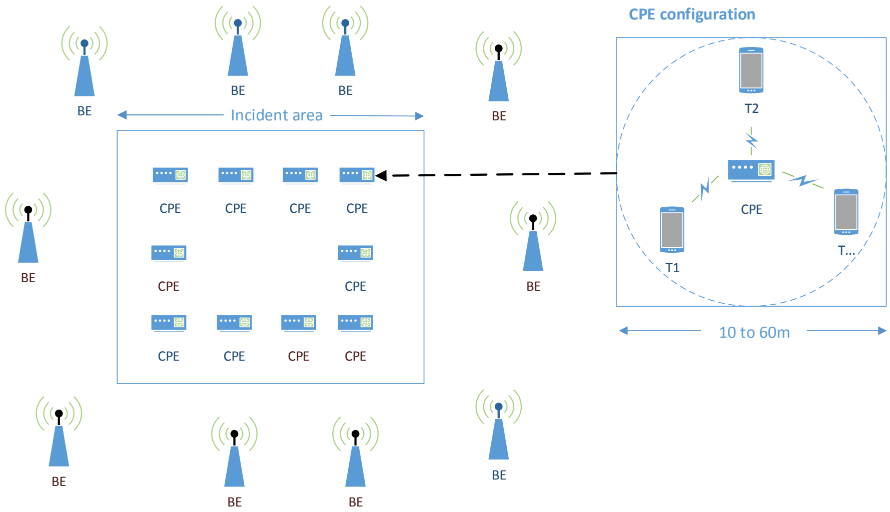

Figure 5.2: Network Architecture Layout

As shown in the diagram above several base stations are arranged around the "incident area" aiming to provide wireless coverage in the internal stadium with some overlap outside of this zone. A maximum of 10 base stations were used with at most 2 CPE's per BE with each CPE supporting up to 20 clients. Early simulation runs attempted use of more CPEs per base station but were unable to reach the required performance /throughput for such results to be useful, therefore as a result each base station is linked to a maximum of 2 CPEs.

5.4.5 Simulation results

Results for the planned scenario section are presented within this section with discussion/analysis. These results assess the following in terms of performance characteristics –

- Throughput – Mean throughput for relevant applications per user.
- Mean packet delay : average delay or latency for packet delivery from the user terminal to the core network measured per application
- Jitter – jitter performance is measured for VoIP application performance to assess network performance.
- Packet delivery performance – Measure of the average number of packets which are transmitted/received to ascertain capability of the network to route traffic effectively.

5.4.5.1 Video results

One of the next generation applications and not currently a widespread application, performance here could be of crucial importance for the mid to long term in PPDR networks. Results are shown in this section for the performance achieved for 50, 100, 150 and 200 nodes with the varying background traffic levels, taking into account the metrics noted above.

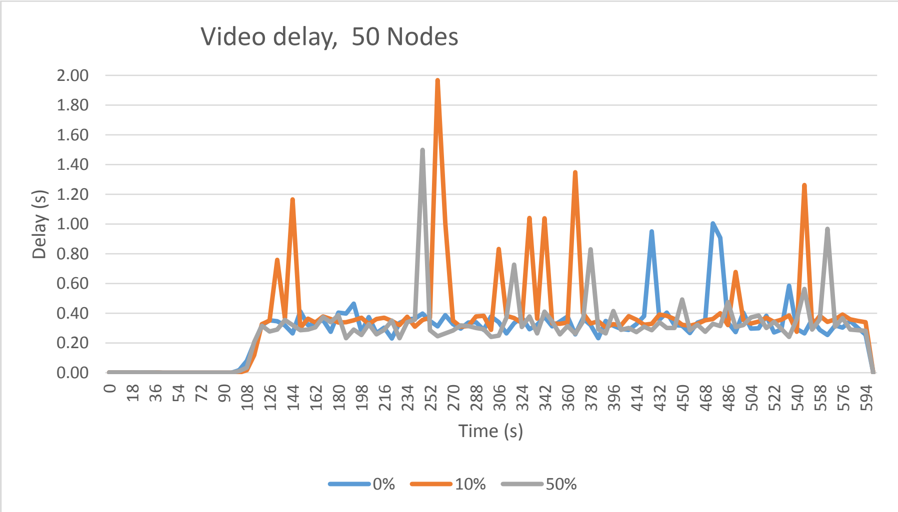

Figure 5.3: Video Delay for 50 Nodes

Highest peak delays are seen with 10% background traffic indicating that the network struggles to provide consistent performance even with the lowest number of users simulated. Performance on average is very similar for all levels of background traffic and 0% provides the best overall performance as in the figure above. Delays above 1s are infrequent at this network load but the highest number of peaks is seen for the 10% test.

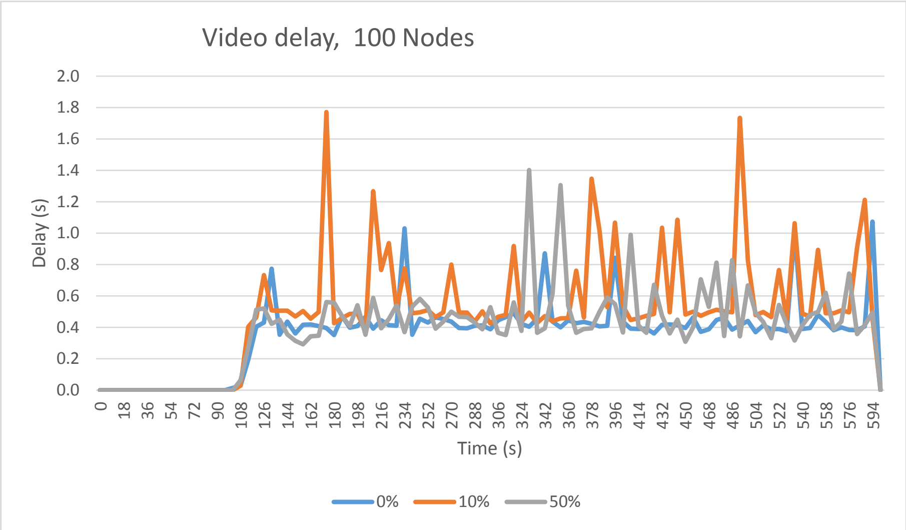

Figure 5.4: Video Delay for 100 Nodes

Video delay performance for 100 nodes shows an increase on average across all background traffic levels with a 20% increase to all users for this application. Overall latency for this application is far more erratic than was shown in the 50 node tests and shows that the network struggles to provide adequate performance for the video application.

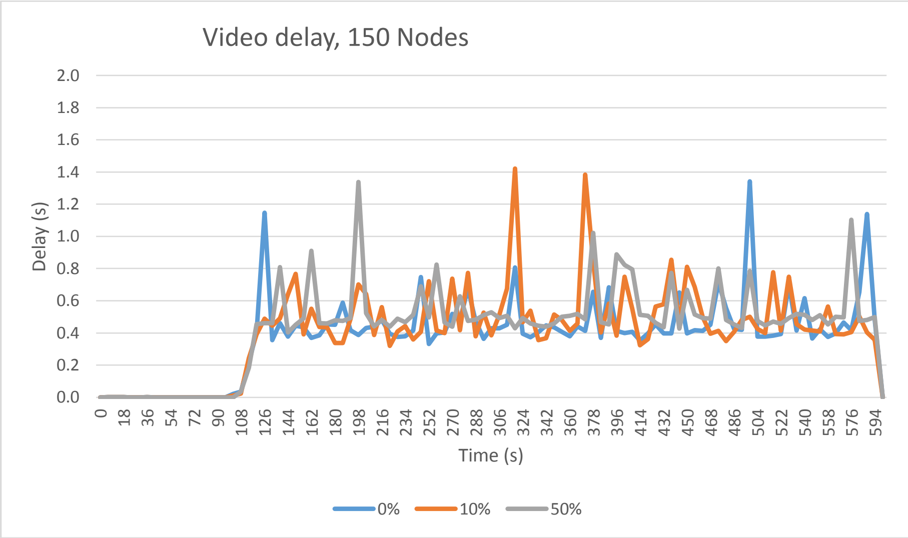

Figure 5.5: Video Delay for 150 Nodes

With an increase in users of 50% the average delay appears similar to the previous test with the extreme values actually being lower, this will be investigated further as this is contrary to what would be usually expected as the number of users & network load is increased.

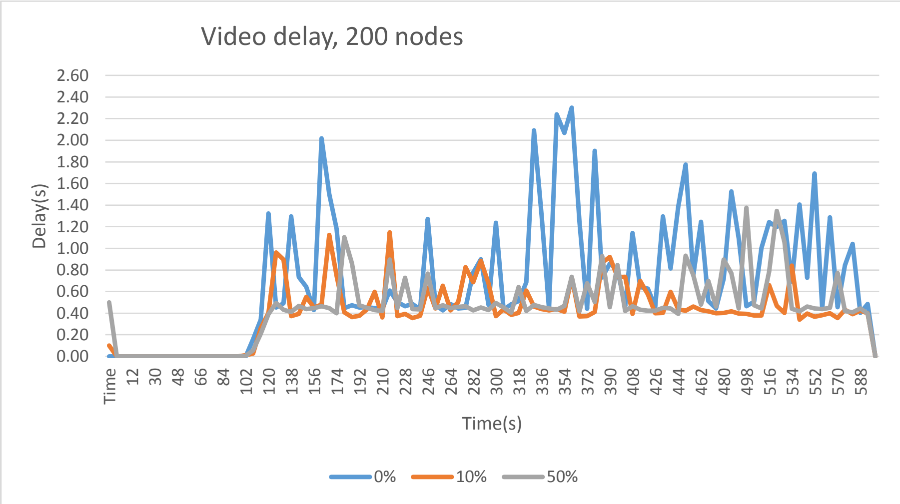

Figure 5.6: Video Delay for 200 Nodes

With the highest number of users in the network, max average delay times are further more increased in comparison with the previous test and as shown in the table below the lower delay for 10%/50% is not due to performance increase but QoS profiling. From a user perspective the delay average of ~1s would still be acceptable to users able to stream video in most situations, for those in time critical situations however this could pose a problem.

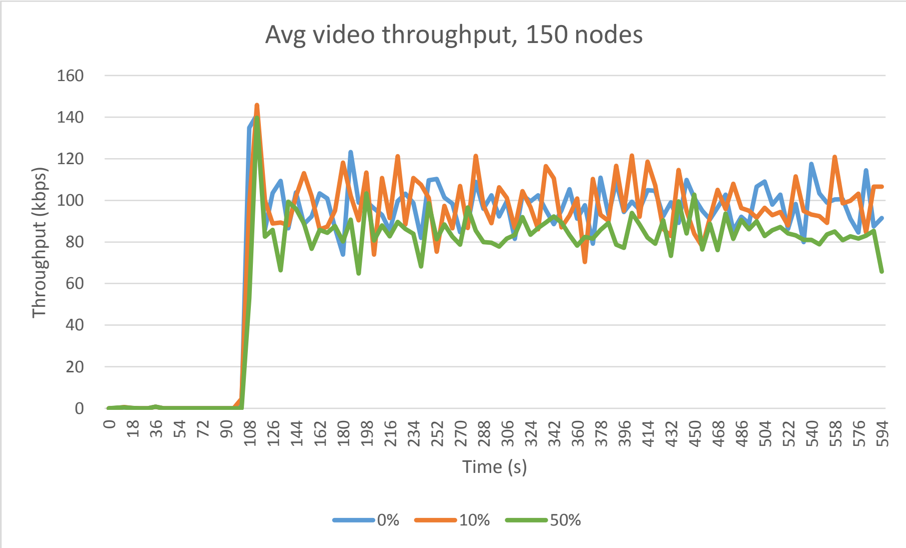

Figure 5.7: Average Video Throughput for 150 Nodes

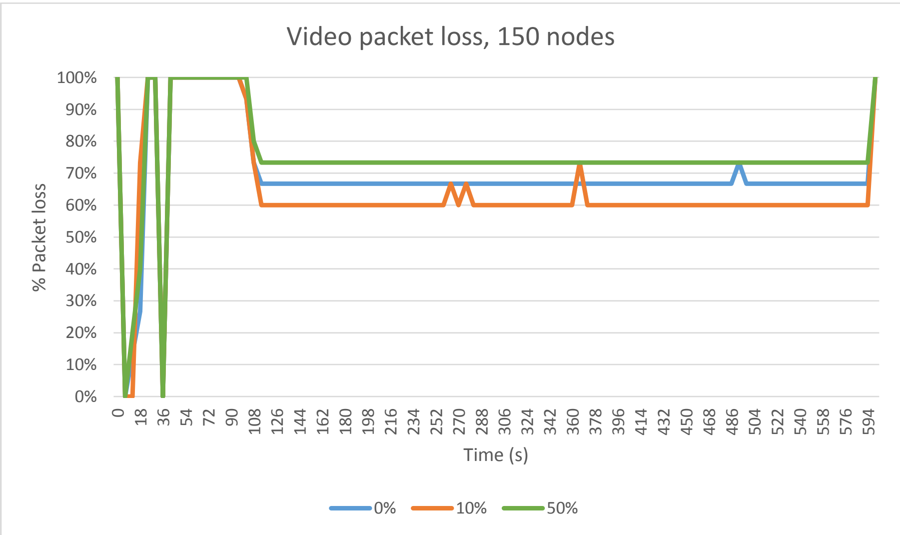

Figure 5.8: Video Packet Loss for 150 Nodes

For the 150 node test further tables were generated from the simulation data sets that included the average video throughput per user and the packet loss ratio for nodes at different background traffic levels. From Figure 5.7, it appears that with the highest level of background traffic the throughput per video user has decreased rather than remained constant, this indicates that there is packet loss occurring due to the QoS profiles prioritising other traffic leaving insufficient bandwidth to maintain the required bit rate to stream video for all users. Packet loss is highest (at 73%) when background traffic is 50%, packet loss is actually lower at 10% which from the upcoming table is a result due to there being 7% more video users able to transmit data in this simulation. This is a small variation and due to the random error margin within the simulator.

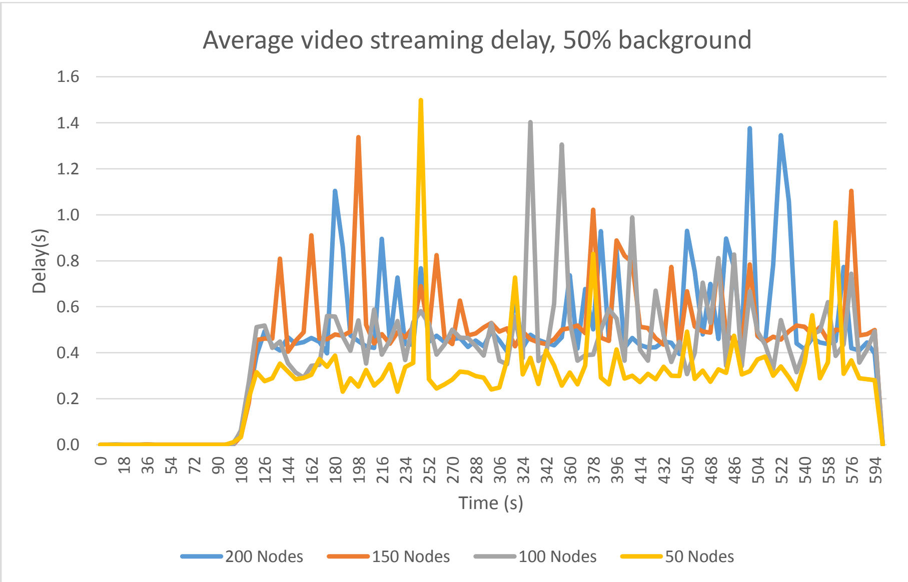

Figure 5.9: Average Video Delay for 50% background

Performance in the table above shows how video application delay is affected as the network size increases when 50% of users are using background applications/data. As can be clearly seen delay performance is lowest with 50 nodes and gradually worsens as the network grows. Performance appears very similar for network sizes of 100,150 and 200 nodes with many peaks in response time mainly due to the QoS profile used to ensure that VoIP performance does not suffer.

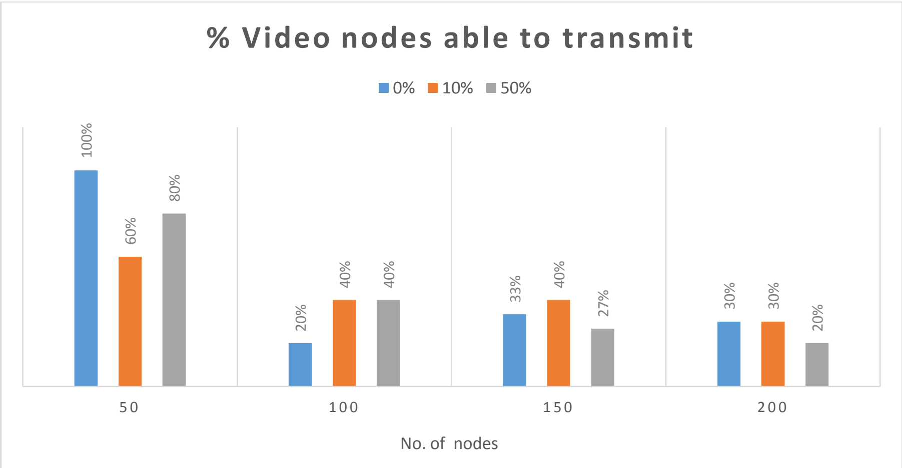

Figure 5.10: Percentage of video able to transmit for all nodes

This table above was generated after noticing that the overall delay performance in some network sizes/background traffic levels was actually better as the network size was increased/background load (0%, 10% & 50%). Here it can be seen that in order to meet the require QoS profile requirements for VoIP that there was not sufficient capacity in the network for use of the video application, thus such users were unable to transmit any traffic in these cases (reducing the overall network throughput in these situations whilst also allowing for potentially better delay performance due to less video users sharing the remaining available bandwidth). Here only in the lowest network size of 50 nodes with 0% background traffic were all allocated users actually able to successfully stream video, as this background traffic increased this generally is reduced or remains static and performance at higher network sizes becomes even worse with very few users actually able to stream video. Thus in this respect the WiFi with WiMAX backhaul is unable to meet the requirements of the PPDR network except in very small numbers (limited to 50 users).

5.4.5.2 VoIP Results

All results and graphs are provided for the VoIP application in this section. VoIP performance will be analysed taking into account some example Service Level Agreement (SLAs) for networks providing VoIP services. The table below details these parameters in terms of maximum delay (latency), max jitter and allowable packet loss.

Table 5.11: SLAs Network Requirement

Network SLA	**Max latency**	**Max jitter**	**Packet loss (max)**
Axiowave	65ms	0.5ms	0%
Internap	45ms	0.5ms	0.3%
Qwest	50ms	2ms	0.5%
Verio	55ms	0.5ms average, not to exceed 10ms max jitter for more than 0.1% of the time	0.1%

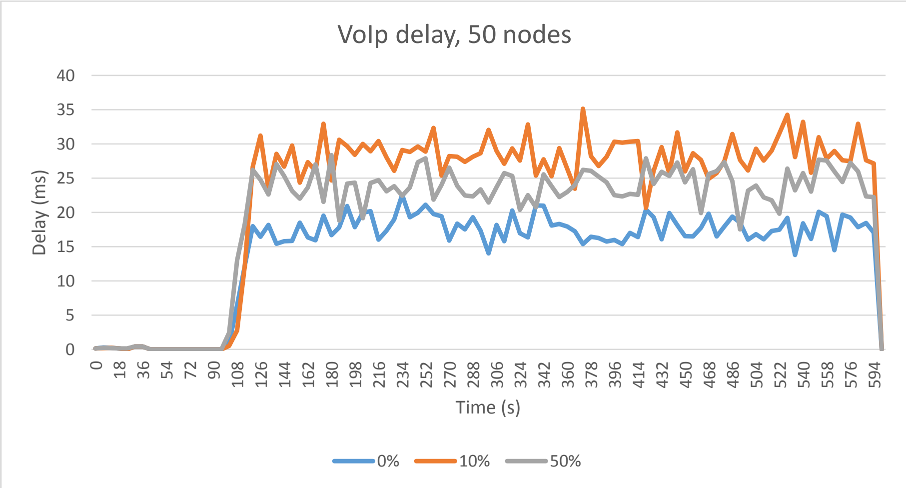

Figure 5.11: VoIP Delay for 50 Nodes

In the above graph it can be seen that VoIP delay between various background traffic levels is quite close (5ms offset) and performance is best when there is 0% background traffic as expected. Performance between 10% and 50% delay although < 10ms on average is slightly improved with a higher network load. Latency performance is more than 20% lower than the lowest maximum allowed latency (Internap) and thus within an acceptable range for PPDR users.

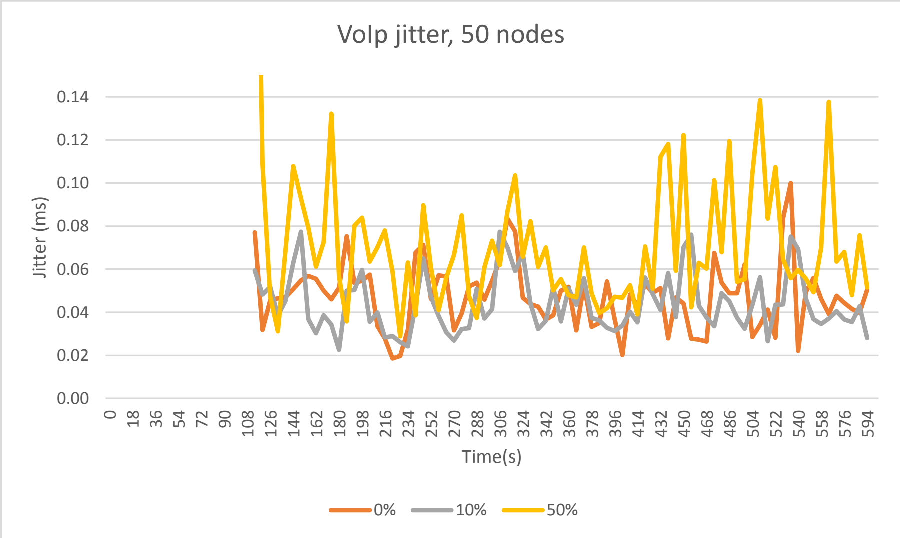

Figure 5.12: VoIP Jitter for 50 Nodes

Jitter performance meets the required criteria for all previously mentioned SLAs in the earlier table, and therefore offers acceptable performance for PPDR users.

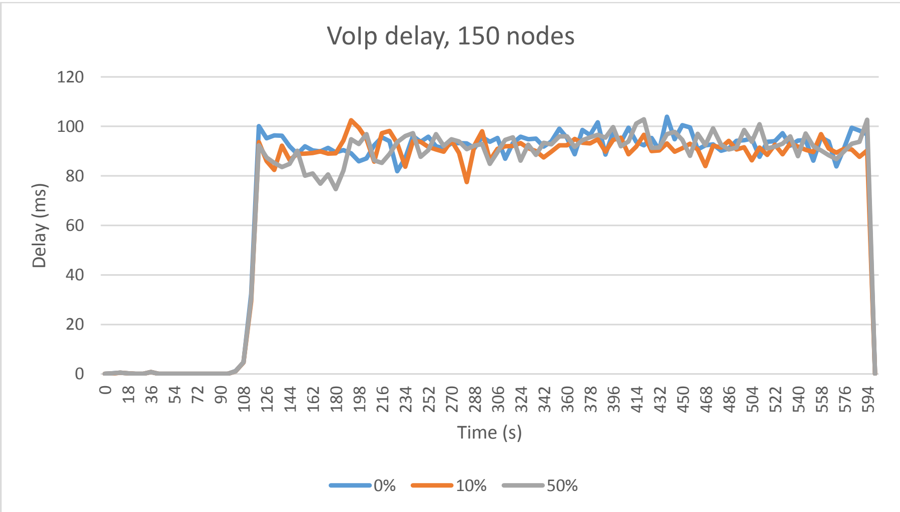

Figure 5.13: VoIP Delay for 150 Nodes

With the increase in network size to 150 nodes latency performance has become significantly degraded and would be deemed unacceptable for all network SLAs. Background traffic appears to have minimal impact on the delay times and thus not deemed to the cause of the high delays, this is simply related to the amount of nodes in the network and down to allocating QoS profiles across this number of users.

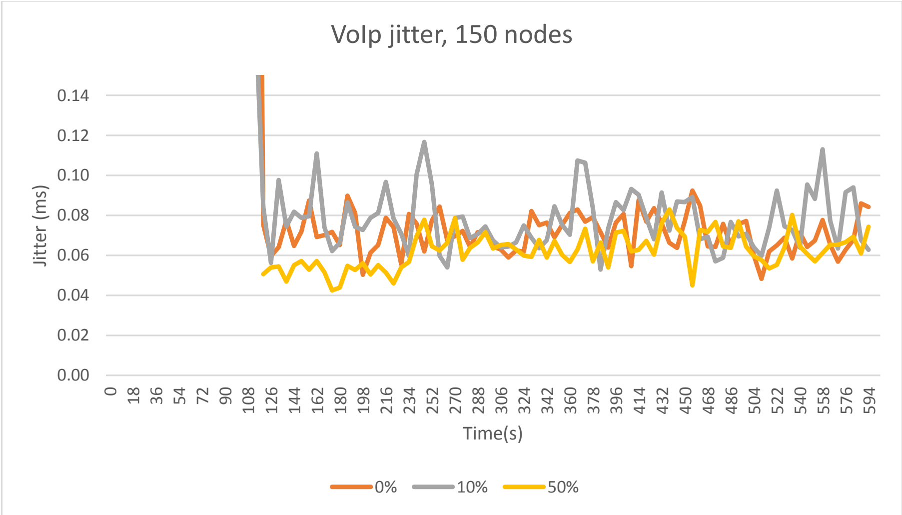

Figure 5.14: VoIP Jitter for 150 Nodes

Jitter performance for 150 nodes is similar to that obtained with 50 nodes and is well within the acceptable bounds for the network SLAs, background traffic again has minimal impact on jitter performance and is not seen as a problem for the network as a whole when considering this performance metric.

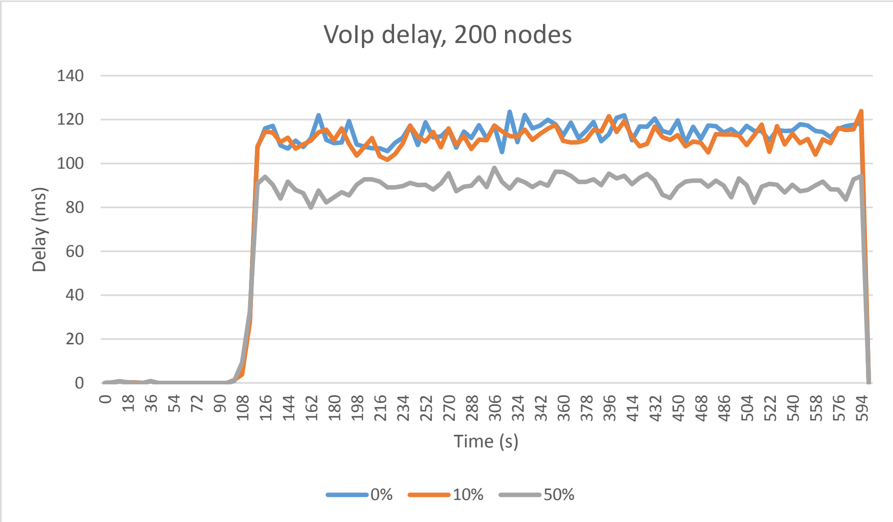

Figure 5.15: VoIP Delay for 200 Nodes

With the final increase in number of users the performance is still above the acceptable network SLAs for all background traffic levels. Unusually at 50% background traffic VoIP performance actually improves, this would appear to be related to the number of video users (largest generator of network traffic) being reduced in this scenario due to the increase in traffic from FTP in order for the QoS profiles to reduce loss to VoIP/FTP and web traffic.

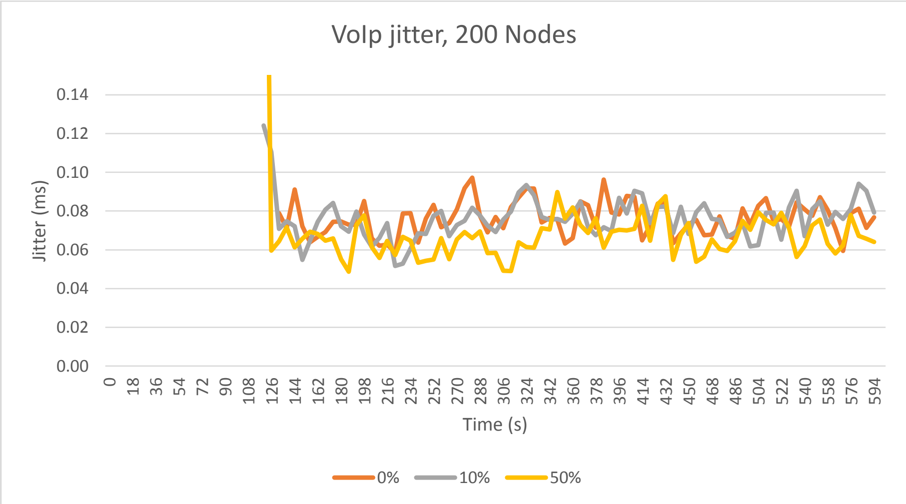

Figure 5.16: VoIP Jitter for 200 Nodes

Again acceptable jitter performance is observed here meeting the required SLAs, though latency performance is clearly inadequate so unable to meet the requirements for PPDR users. Performance levels at both 150 & 200 nodes shows a significant/unacceptable delay to VoIP traffic which will degrade the user performance significantly. Although delays in video and web applications are far higher, VoIP has much lower tolerances which when exceeded provide an unusable user experience and would therefore be unsuitable for PPDR use. Reduction of background traffic generally has minimal effect on VoIP and therefore is not the core cause of the increased delay, jitter performance was acceptable and would not require any changes. Recommendations would be to optimise network QoS profiles to minimise use of higher bandwidth applications such as video streaming to ensure that adequate VoIP performance might be achieved in larger network sizes.

5.4.5.3 Other results

This section contains the remaining graphs detailing average throughput per user, performance in web application and packet sent/received ratios and other relevant data.

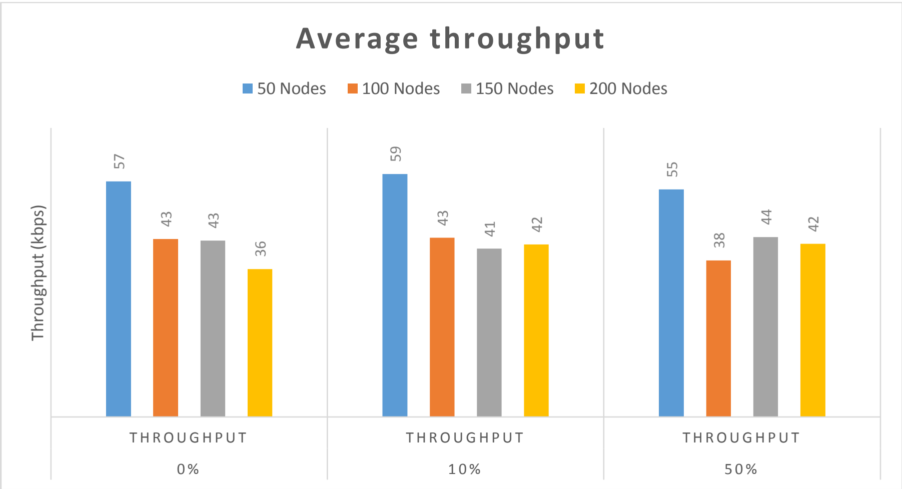

Figure 5.17: Average Throughput for all nodes

The graphs above present the average throughput for each configuration tested in the simulations for this scenario. As can be seen on average the performance for node throughput decreases as the network size increases. Indicating that the network is unable to cope with the traffic generated by these nodes with a maximum throughput of only 59Kbps this is likely to be wholly inadequate for next generation application users, this average bit rate would be just shy of the 64kbps required for VoIP communication using G.711.

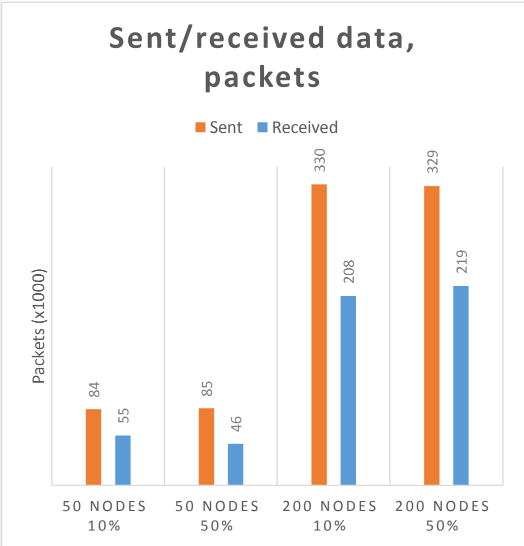

Figure 5.18: Packets Sent/Received for 50 and 200 nodes

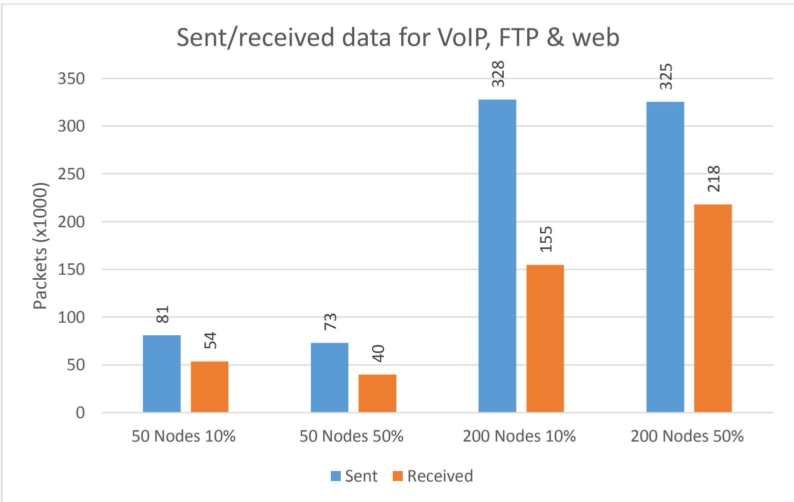

Figure 5.19: Packets Sent/Received for VoIP, FTP and Web for 50 and 200 Nodes

The figure above shows the overall number of packets sent & received for all traffic types excluding video. On average as the network size increases (and also the number of base stations) the data sent increases in proportion of the number of users. From the graph below the performance in terms of packets sent/received is fairly consistent across each network deployment indicating that the load at each CPE is very similar and the limitation is as a result of lacking capacity at the base station.

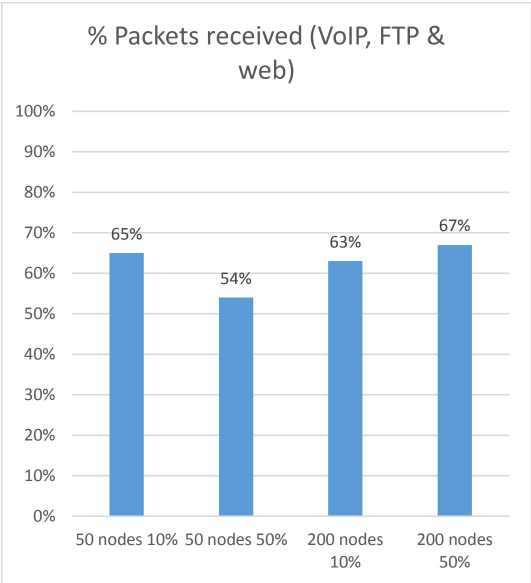

Figure 5.20: Percentage of Packets Received Excluding Video

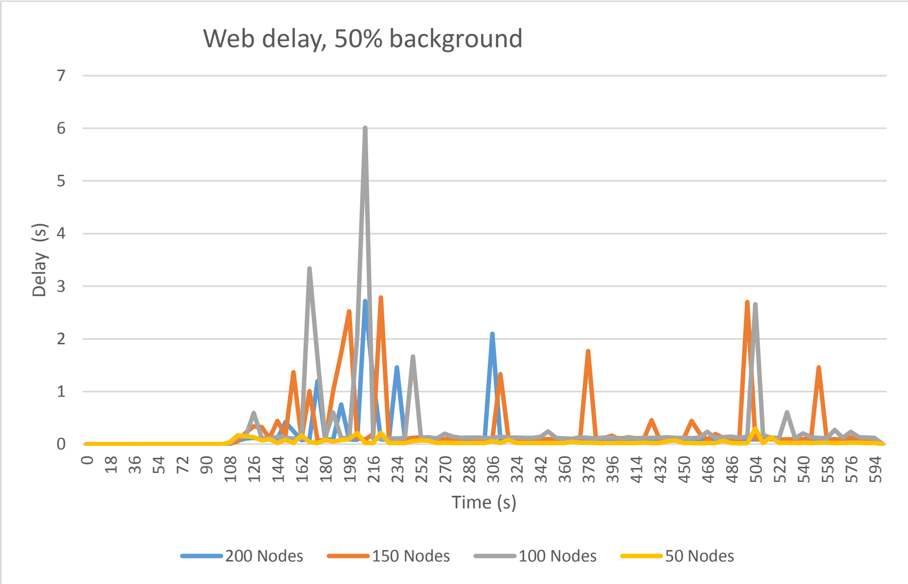

Figure 5.21: Web Delay for 50% background

With a static background traffic of 50% it is clear to see that the network performance is more or less stable where the network size is 150 nodes or lower. With the configuration used for this simulation WiMAX is not truly able to provide an acceptable user experience with delays of up to 6 seconds, performance with other network sizes would be suitable on the whole with the occasional blip in performance.

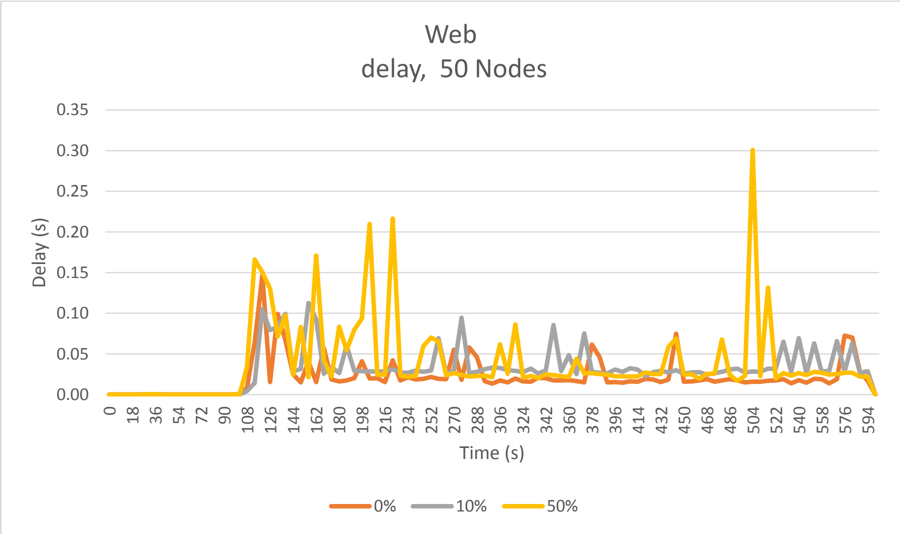

Figure 5.22: Web Delay for 50 Nodes

Web page performance is shown to have increasing delays for some users with higher background traffic which would degrade performance for some users in the network, however with page loads of well under 1 second across the 50 node network this would be very good performance for PPDR services.

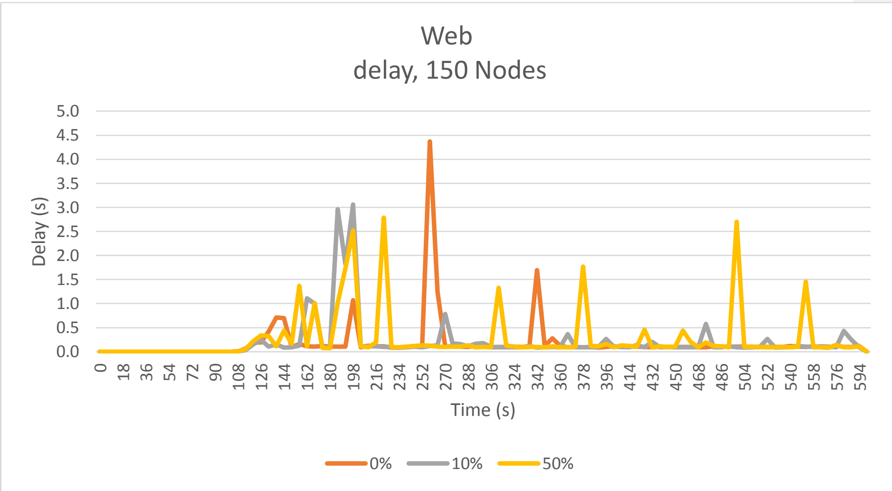

Figure 5.23: Web Delay for 150 Nodes

With an additional 100 users added to the network performance of the web application is significantly worse. Performance across various background levels shows a higher number of peak delays with more network traffic with the occasional anomaly though on average the performance is well under 1 second and would provide good performance for PPDR network users for the majority of the time.

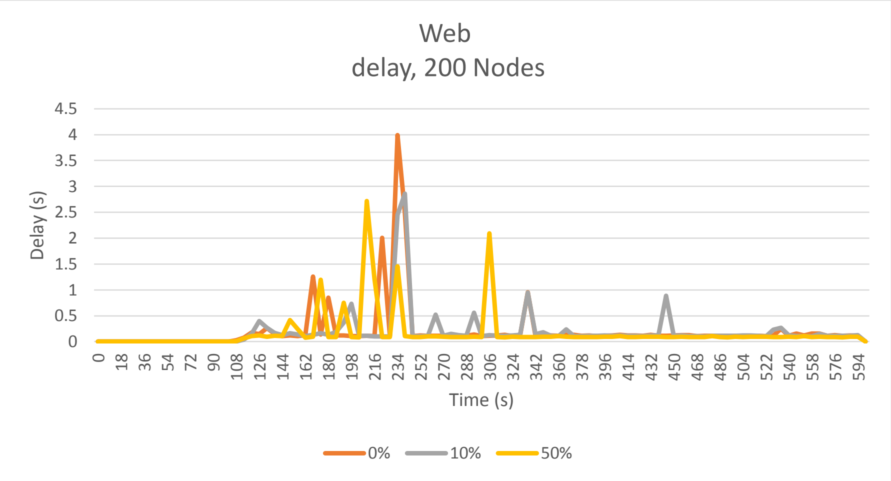

Figure 5.24: Web Delay for 200 Nodes

Application latency and web performance in the largest network size shows an overall increase in the average delay with slightly more erratic performance, however on the whole response time is adequate for an acceptable user performance in most cases. As previously seen, response times are subject to higher delays or more inconsistent performance as background traffic increases, this places load on the QoS profiles in attempting to meet the desired performance requirements despite, as has been clearly shown lacking the required network capacity. In these simulations it is shown that only with a smaller number of users is performance consistent across the simulation time, with the traffic demands that 150 and 200 nodes place on the infrastructure it is unable to provide the requirements of the network and thus PPDR users.

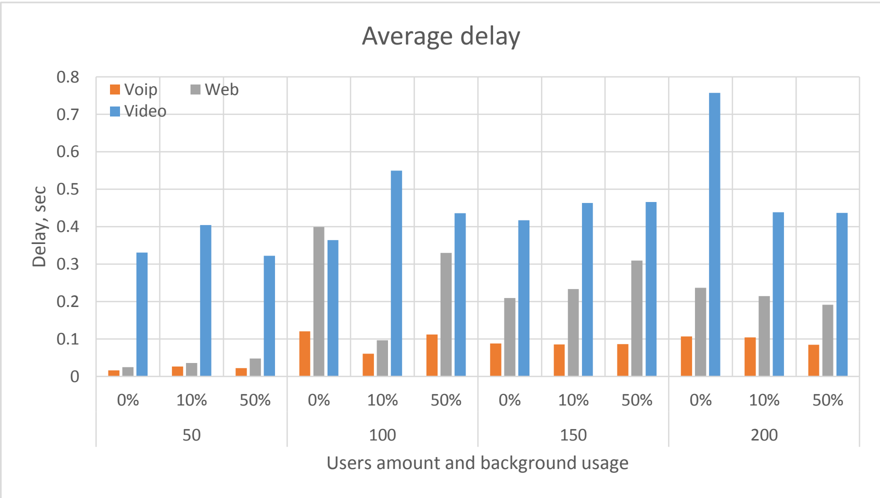

Figure 5.25: Average Delay for VoIP, Video and Web for all nodes

5.5 Additional Results Analysis and Conclusion

Video Results

Based on the graphs of 0% of FTP background traffic, performance of delay is acceptable. This is what is expected as the number of nodes are expanding, delay is also increased. However, for 10% and 50% background traffic, it keeps decreasing as the nodes are getting larger. This is because, when the network load is getting heavier, there are some of the video users that are unable to be granted the requested bandwidth which affects the results. Next, we examined the throughput results, focusing on the 150 nodes as an average performance of the total network. The graphs show that for 0% and 10% background traffic, the results are almost similar which is around 120 kbps since there is not much difference of background traffic between them. Meanwhile, it was contradicted for 50% background traffic, showing the lowest throughput at the average of 80 kbps due to more users in the network. Since the throughput drops, we measured the packet loss as depicted in the figures. Result shows that the highest percentage of packet loss happened to the 50% background traffic, which is what we expected based on the previous performance. In order to understand more what is happening in the 50% background traffic, we looked at the details of the delay performance for all the nodes. It is clearly shown that the lowest delay is from the 50 nodes and it gradually increased as the netwok grows. Lastly, to find out which nodes perform the best or optimum video results, we plotted graphs of how many video users are able to transmit for each different background traffic. As we can see that, the lowest nodes (50 nodes) has the highest percentage of successful video transmission compared to other nodes. Also to mention, the 100% achievement is obtained by the 0% background traffic in the 50 nodes user. Thus, as the conclusion for the PPDR requirements, the best performance goes to 50 nodes.

<u>VoIP Results</u>

Since VoIP is a highly delay insensitive application, we only focused on delay and jitter results as described in figures. Taking into account results for all percentages of background traffic (0%, 10%, 50%), performance of delay are getting higher as the nodes increased. Since more VoIP users were added in the network, the delay is expected to increase as well. However, delay higher than 65ms which is referring to the maximum delay accepted in network Service Level Agreement (SLA) is not applicable to the PPDR operation. Thus, in this scenario, it is only acceptable for the 50 nodes user. In this result, we did not include results of 100 nodes since there is not much difference compared to the other nodes. Next, we evaluated the performance of jitter for the same nodes. Eventually it shows that jitter for all nodes are within the maximum jitter range mentioned in the SLA, eventhough results for 100 and 150 nodes could not be counted as they exceeded the delay requirement. As the conclusion, to fullfill the PPDR requirements, VoIP performs the optimum results for small nodes (50 nodes).

Web Results

As shown in the graphs, delay for all nodes are growing especially to the maximum of 200 nodes. The result also applies to the different percentage of background traffic. In spite of that, the results are only consistent for 50 nodes users compared to others. Therefore, again it shows that with the smaller number of users, it was able to accomplish with the PPDR requirements.

5.6 Summary

In this chapter, a detailed research has been explored on a hybrid network, which involves integration of WiFi and WiMAX particularly in our scenario. Thus, to evaluate the QoS performance, we investigated the number of WiFi responders/users that could optimize the bandwidth in the network. As the outcome based on the simulations, we proposed the optimum or ideal quantity of WiFi users which had been explained in this chapter. On top of that, we also developed the optimum traffic or application combination that could assigned to the WiFi users and can be applied to the PPDR services for their operation as first responders in an emergency situation.

Chapter 6: Optimization for Integration of WiFi and WiMAX Network for PPDR Services (Unplanned Event)

This chapter is continuously project from the previous chapter which involves with the PPDR Services. However, this chapter will focus on the Unplanned Event Scenario.

6.1 Introduction

Unplanned Event is a situation when the communication infrastructure is deployed when the existing backbone connection is not functioning or destroyed. Therefore, it needs to be link to a communication model which is describe detail in the next section. However, we choosed 200 users in this scenario as our references to evaluates the performance of the network.

6.2 WiFi to WiMAX (backhaul) Unplanned Event

Previously assigned in the preliminary report for "Preliminary technical validation of future PPDRs technologies and architectures". This simulation represents the results produced for a WiFi network using WiMAX as backhaul to a PPDR centre for an unplanned scenario lacking in terms of existing infrastructure/IP backbone. Within this simulation each WiMAX base station is linked to WiMAX CPE's (explained in previous chapter) and this can be up to 1km from the nearest base station. Base stations are simulated as mobile vehicles with a built in mast and represented using appropriate configuration. WiFi users are placed around the WiMAX CPEs and represent the network being deployed at a specific incident site which requires communications infrastructure on an "as required" basis, then using WiFi terminals they access the WiMAX CPE which in terms links to the IP backbone linked to the PPDR centre.

6.2.1 Application modelling

Applications run within this simulation are allocated as per the table included below. Each application is allocated to the number of users indicated per the PPDR users/nodes and will be configured as set forth in the simulation configuration section. Performance is assessed against application delay, packets received ratio of all data sent and jitter for VoIP performance. In this simulation background traffic is fixed at 10% to represent use of other PPDR services used for management purposes/network management etc. As a next generation service it is expected that video streaming would increasingly be required and the effects were compared when increasing the number of video users from 10 % to 30%. OPNET was used as the simulator of choice for these simulations and further detail/justifications can be found in "Specification of validation scenarios and tools **(D5.1 REFERENCE**)"

Table 6.1: Users breakdown traffic

PPDR users/nodes	**Traffic type/application**	**Technical data**
10%, 30%	Video	See below.
40%	Reliable, burst (web)	See below.
70%	Audio (VoIP)	See below.
10%	Reliable, continuous background (FTP)	See below.

From the table above the breakdown of traffic is allocated between all users/clients in the simulation. The breakdown of traffic/applications per user is shown below for each of the simulations;

200 users 10% video

- 20 video users
- 80 VoIP users
- 20 VoIP & FTP users
- 40 VoIP & web users
- 40 web users

200 users 30% video

- 20 video users
- 40 video & VoIP users
- 40 VoIP users
- 20 VoIP & FTP users
- 40 VoIP & web users
- 40 web users

As described above the majority of users are using one or two applications simultaneously with VoIP being the core application, as would be representative in a PPDR unplanned scenario. FTP traffic is generated at the lower level 10% in this scenario as this network would be a private network only used by PPDR users and thus the level of additional traffic would not be as variable compared with for instance the planned scenario. Here network traffic and application performance is monitored as the number of video users are increased to assess performance impacts for VoIP performance as the most important traffic type used currently by PPDR users.

Video streaming was represented using the built in OPNET feature for video streaming and generated a standard bit rate of approximately 140kbps depending on available bandwidth and network capacity. Using this reference video streaming the frame rate was reduced to ensure the bit rate was constant and that the throughput performance can be assed against bandwidth requirements of various other video streaming codecs. Video application configuration is described in the table shown below;

Table 6.2: Video application configuration

Video Application	
Frame size	10 Kbytes
Frame rate	10 fps
Video codec emulated	H261
Operation Mode	Always ON (Serial ordered))
Minimum bit rate over WiMAX	140kbps
QoS Type	rtPS

The VoIP application is one of the crucial traffic types for users and was therefore allocated as a high priority Quality of Service (QoS) profile using UGS (Unsolicited Grant Service) which guarantees a constant bit rate (set at 96 kbps) with minimal delay which is crucial for voice communications. In this instance the codec used was G.711 for all forthcoming simulations with a fixed max bit rate of 64kbps.

Table 6.3: VoIP application configuration

VoIP Application	
Encoding	G.711
Compression delay	0.02s
Decompression delay	0.02s

Operation Mode	Serial Random
Max bit rate over WiMAX	64 kbps
Min bitrate over WiMAX	96 kbps
QoS Type	UGS

The final two applications were to represent random/unpredictable requests for bandwidth in a random/burst manner. For this web browsing was chosen as often, webpage requests may be made in this random and unpredictable way. FTP traffic is used to represent an overall background traffic for applications and services which would be used by PPDR agencies for anything not related to video or voice. In this scenario the constant load was set at a constant 10% and results were compared against the number of users using higher bandwidth applications (video).

Table 6.4: Web browsing application configuration

Web browsing application	
HTTP Specification	HTTP 1.1
Object size	Constant 500 Bytes
Operation Mode	Serial Random

Table 6.5: FTP application configuration

FTP Application	
File size	50 Kbytes
Inter-Request Time	Exponential 360 seconds
Operation Mode	Always ON

6.2.2 *Simulation configuration*

Herein this section the technical description and configuration of the communication technology is provided. For the unplanned simulation it is envisaged that the infrastructure would deployed as required in the area of the unplanned incident, this area was deemed to be 10km x 10km for the purposes of this simulation.

Here WiMAX base stations are represented as mobile base stations which would be deployed from a vehicle and fixed into place for the duration of the simulation, potentially in a real world incident they could move between locations to offer the best coverage for individual areas as necessary. Each CPE would be deployed locally at an incident site and relocated as necessary, this could be several km from the deployed base stations and further still from the PPDR command centre which is linked using the WiMAX backhaul to these users. In order to provide a representative set of results in a reasonable time this simulation focused on a 10km square whereby up to 200 users would be deployed representing a fairly dense coverage when placed into the 40km overall area.

- WiMAX base station: Each system is deployed into a mobile vehicle with large mast for communication with other systems. The network would require some initial configuration when arriving on site to be linked with the core PPDR centre using the WiMAX as back-haul IP back-bone. Once deployed WiMAX CPEs could be deployed within several km from each base station and ideally as close as possible to minimise packet loss and improve throughput performance. The technical configuration for each WiMAX base station in the simulation is shown in the table below;

Table 6.6: WiMAX Base Station configuration

WiMAX Base Station	
Operating Frequency	2.5 GHz
Bandwidth	10 MHz, 1024 (subcarrier)
Transmitter Power	2 W
Antenna Gain	18 dBi

- WiMAX CPE: These devices would deployed within 10 to 60m of an incident site to provide necessary network coverage for PPDR users using the nearest WiMAX base station for back-haul connection to the PPDR centre. In this scenario there are up to 20 users per CPE using WiFi terminals with the traffic generating applications already presented, each terminal could represent any WiFi enabled device. The technical configuration used for each CPE is displayed in the table below;

Table 6.7: WiMAX CPE configuration

WiMAX CPE	
WLAN Standard	HT PHY 5.0GHz (802.11n)
Data rate	6.5Mbps to 60Mbps
Antenna Gain	18 dBi
Modulation	OFDM
Max TX Power	3W

- WiFi Client: Representing the PPDR users these devices are placed within range of the WiMAX CPEs and run each of the applications already described. Each terminal generates the user's network traffic and this is routed through the WiMAX CPE→

WiMAX base station and to the core PPDR control centre. The technical configuration used for these WiFi terminals is shown in the table below ;

Table 6.8: WiFi Client configuration

WiFi Client	
Standard	
Data rate	6.5Mbps to 60Mbps
Antenna Gain	18 dBi
Modulation	OFDM
Max TX Power	40mW
Buffer size	32 000Bytes

6.2.3 Simulation layout

Herein this section the network topology of the unplanned scenario is described. For the unplanned scenario WiFi coverage is primarily aimed to provide network access in the immediate area to PPDR users and would be deployed in sites as required dependent on the situation at hand. Each WiMAX CPE would have between 2 and 60m coverage range for WiFi users and would only allow terminals in this vicinity to connect to the core network, in turn this device would connect to the WiMAX base station which would back-haul information to the PPDR central control centre.

Within this scenario the number of overall network nodes was fixed at 200 nodes representing the expected network load in the specific 10km x 10km area for the unplanned scenario, thus ensuring a simulation run time which was not overly prohibitive. This allowed the PPDR simulator to produce results which can accurately represent the network load, interference and network topology across a specific operational area, and thus derive a meaningful performance assessment which can be applied to the larger incident area for various network sizes.

The overall network topology is shown in the diagram below. WiFi terminals (PPDR users) are shown under the CPE configuration section, and there are 20 users per CPE on average.

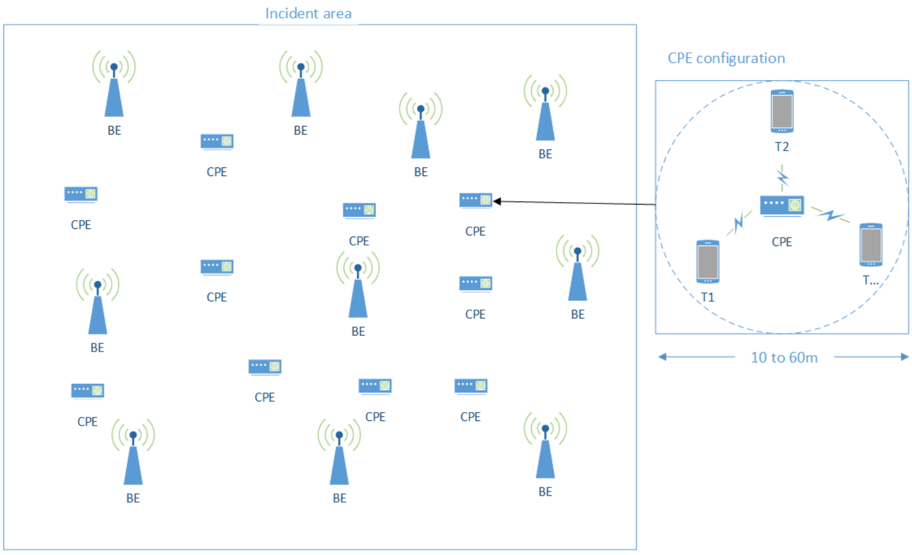

Figure 6.1: Network Architecture Layout

As demonstrated in the diagram above 10 base stations are arranged across the representative incident area with CPEs placed accordingly to allow for connection to the WiMAX network which would then link back to the centrally located PPDR command and control centre. Each CPE providing local coverage to an area requiring PPDR assistance was emulated with up to 20 users per CPE and there were never more than two allocated CPEs to one base station.

6.2.4 Simulation results

Results within the unplanned scenario are presented here with relevant discussion and analysis. Performance is assessed on the following criteria –

- Throughput – Mean throughput for relevant applications per user.
- Mean packet delay : average delay or latency for packet delivery from the user terminal to the core network measured per application
- Jitter – jitter performance is measured for VoIP application performance to assess network performance.
- Packet delivery performance – Measure of the average number of packets which are transmitted/received to ascertain capability of the network to route traffic effectively.

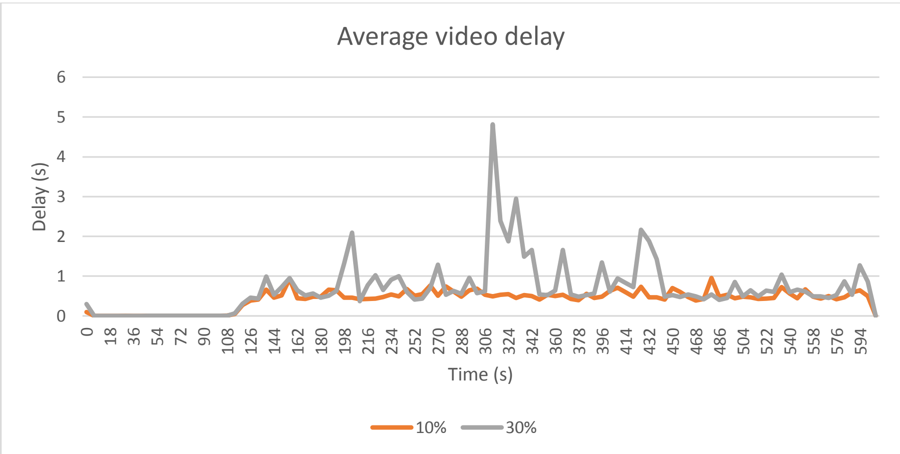

Figure 6.2: Average Video Delay for 10% and 30% background

The simulations were for 200 Nodes with 10% of them using ftp traffic and 10% or 30% using the video. The video streaming delay for scenario with 30% users are using video has significant peaks, while it is more stable when only 10% of users are using video.

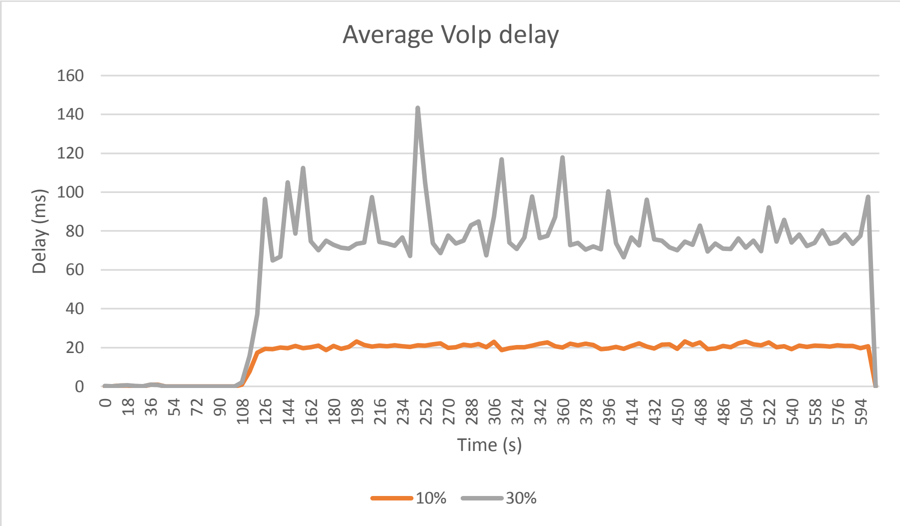

Figure 6.3: Average VoIP Delay for 10% and 30% background

VoIP delay is shown to be well within acceptable performance levels (and network SLAs) at 10% of video streaming users but as this increases is pushed over the maximum 65ms acceptable delay to ~80ms, performance is also unstable at this level and would be of no use to PPDR users in mission critical situations. Thus performance is very good with only 10% of users streaming video and low level background traffic of 10% (fixed in these simulations).

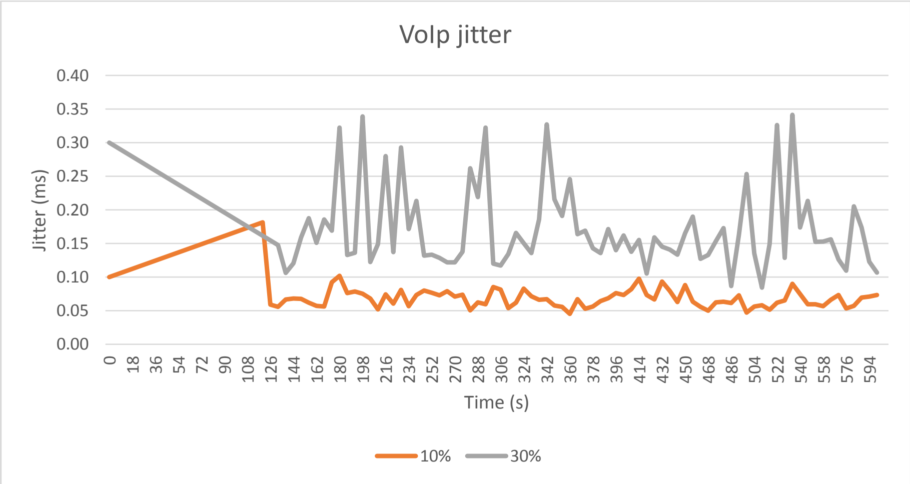

Figure 6.4: Average VoIP Jitter for 10% and 30% background

Jitter in the unplanned scenario is significantly higher with the larger number of video users though still within the 0.5ms threshold for network SLAs. Performance is similar to the planned scenario **(previous chapter)** for 10% video users but is significantly higher with 30% video users, this is in part due to an increased distance on average between CPEs and base stations.

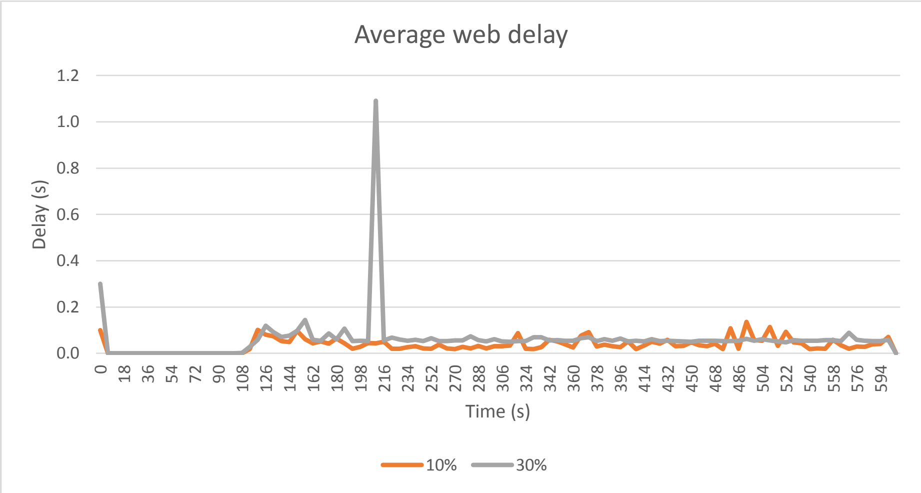

Figure 6.5: Average Web Delay for 10% and 30% background

The delay for the web applications are similar for both of the scenarios, allowing consistent web performance the majority of the time. Response times are well within acceptable levels (well below 4s) and would provide a suitable user experience and be suitable for use with PPDR services to relay information to field units.

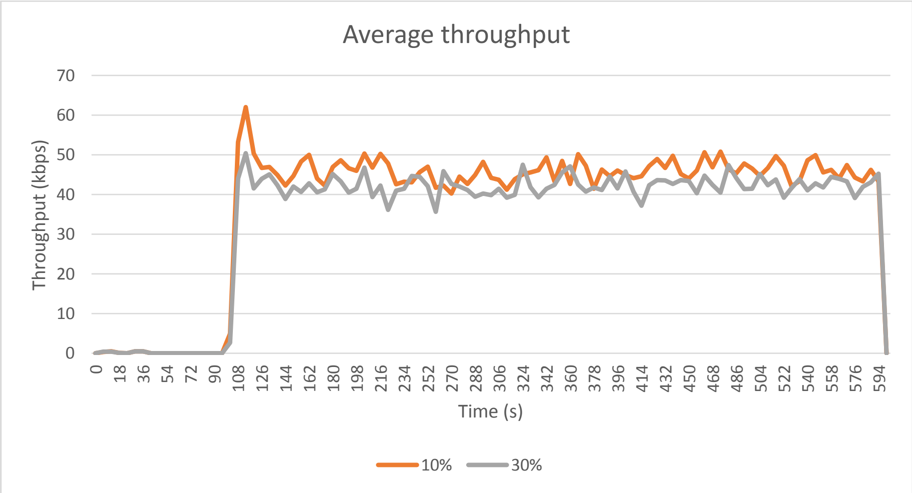

Figure 6.6: Average Throughput for 10% and 30% background

Average network throughput per user is shown to be very similar on average for both 10% and 30% video streaming levels, this is due to reaching the network capacity at 10% and thus higher throughput per user is not possible with more video users. Further to this average throughput is around 40kbps and significantly below the required throughput for loss free, low latency VoIP performance which would require network to never be at 100% capacity (for 200 nodes).

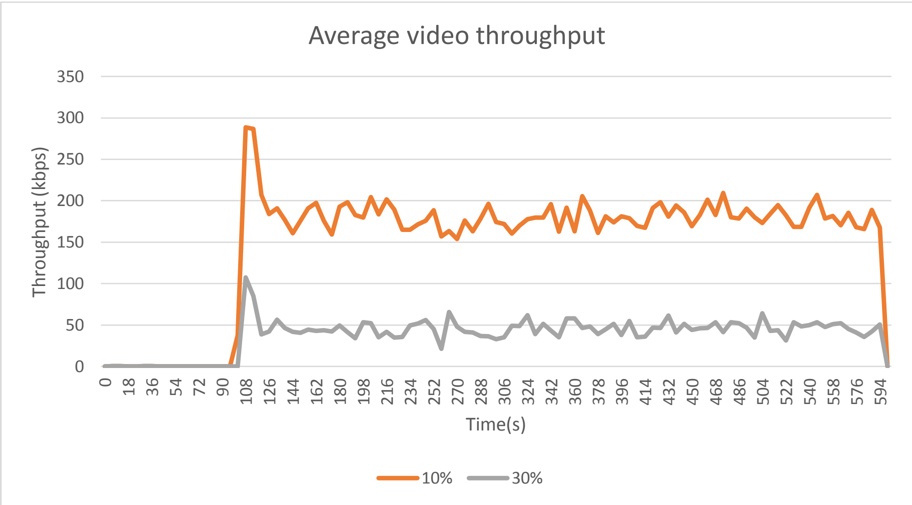

Figure 6.7: Average Video Throughput for 10% and 30% background

The figures for the throughput and the video throughput show that the throughput is predictably decreased when the number of video streaming users was increased. Average throughput is reduced by roughly 70% with the increase in video streaming users and this is due to the network being oversubscribed as demonstrated in the packets sent/received ratios below.

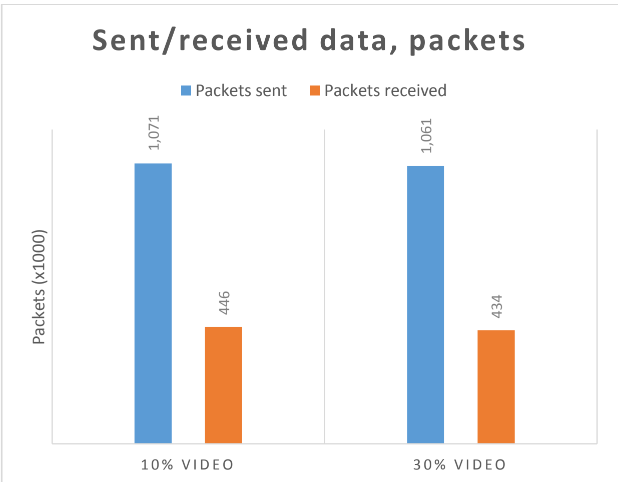

Figure 6.8: Packet Sent/Received for 10% and 30% Video

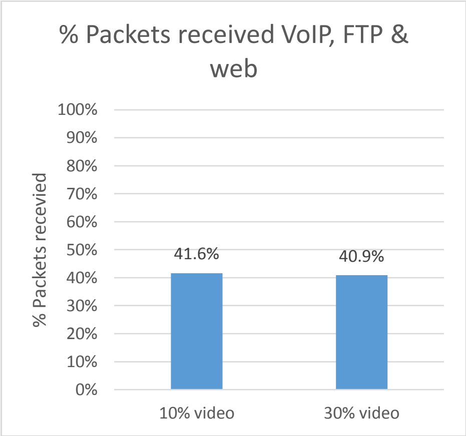

Figure 6.9: Percentage of Packets Received of VoIP, FTP and Web

The graph above shows the overall number of packets received against the percentage that were sent. As is clear performance is very similar taking into account all packets sent for both VoIP and video. In both scenarios with over 50% of traffic being dropped/lost or not received it is clear that the network performance is inadequate and unable to meet the PPDR user requirements for even 200 users.

6.3 Additional Results Analysis and Conclusion

In this chapter, we investigated the performance of locating highest number of WiFi users/nodes based on PPDR requirements. As the matter of that, we also increased the percentage number of video users from 10% to 30% to have a look at the effect on the total network. From the data in Figure 6.2, it is apparent that video delay for 10% video users shows a stable result compared to 30% video users. Next, we had a look at delay for VoIP. Same as previously, the results indicated that only for lower percentage or video users, delays are within the SLA requirement. The same performance also obtained for jitter, which shows that lower jitter is produced for 10% video users. However, the findings of web delay application show slightly a different performance. Delays for both percentage of video users showing a similar output, thus allowing consistent web performance all the time. Another important finding was the network throughput. Average throughput for both percentages ranges between 40 kbps to 50 kbps, however it is significantly lower than the required throughput for PPDR operations. To understand more about the network performance, we also plotted a graph for percentage of packets received based on number of packets sent and received. The percentage of packets received mainly for VoIP, FTP and web application since adding the video users will degrade the network performance. Comparing the two set of results, it can be seen that over 50% of the traffic was dropped due to the network load. As the conclusion, considering all the results obtained for 200 users with different percentage of video users, the network was unable to satisfy the PPDR requirements.

6.4 Summary

Based on the previous chapter, the maximum number of users in the scenario is 200. Therefore, in this chapter, we investigated more about the performance of the 200 users when number of users assigned with the video application is increased. The results presented has shown that the QoS network parameter is affected when more video users are present in the network. This happened since more bandwidth is allocated for video as compared to others, which increased the network loss as well. However, since most of the results showed unsatisfied results based on the PPDR requirement, therefore an increase in video users will degrade the network performance.

Chapter 7: Conclusion and future work

This thesis is dedicated to the development and optimization of the disaster operation applications, particularly focusing on PPDR research project.

7.1 Contribution To Knowledge

The main contribution to knowledge is the development of hybrid network consists of WiFi + WiMAX, which can guarantee QoS in disaster situations. Generally, we consider two key components of these systems: wireless hybrid networks and users' application algorithms. Also, I introduced new algorithms which provide significant improvements compared to conventional systems as an addition to my contribution.

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When researching wireless hybrid networks, we introduced the concept of end-to-end heterogeneous QoS and provide optimized solutions for the two most widely used HN: WiFi+WiMAX and WiFi+LTE as presented in Chapter 3. For these systems it was illustrated how the system parameters changed, depending on the information transmitted with the various QoS classes, through a hybrid network. A major parameter in the functioning of the presented networks is the throughput achieved by the user. The simulation provided us with the following conclusions - QoS maps were developed to optimize the end-to-end parameter. All simulation results were presented and analysed. The outcome presented that, depending on the network loads, the worst class of QoS priority is the best option for the user. This was explained not only with theory, but also with a practical explanation using actual parameters of hybrid network.

In the WiMAX as the homogeneous system research, we proposed a new approach for QoS mapping table as discussed in Chapter 4. We assigned different QoS to different applications to investigate the network performance. The results presented in this thesis has illustrated that the developed approach is applicable to the first responders especially in an emergency situation.

While conducting the integration of WiFi and WiMAX project, which was reported in Chapters 5 and 6, we found out that users' application played an important role in the bandwidth utilization. Therefore, to allow more users in the hybrid WiFi+ WiMAX network, we proposed users' application algorithms for the Wifi users. It applies the proposed models optimize the bandwidth alongside with the minimization of delays and packet dropped. Also, various simulations tests were conducted to verify the number of Wifi users could accommodate in the hybrid system as required by the PPDR operations. The results presented in this thesis showed that there are some limitations for the users based on a specific parameters and scenarios. The results have been proposed to the European Union project in the framework of the program EU FP7 SEC under PPDR-TC grant agreement.

7.2 Limitations and Critical Reflections

During my research in order to achieve the overall objectives, there were some limitations and critical reflections. In terms of interference problem, the suitable WiFi standard needs to be chosen in order to have all the CPE working successfully. Therefore, in my research, I found that 802.11n was the best standard to use. Another concern is the number of CPEs in the scenario. It would be better if the number of CPEs could be reduced, which will eventually minimise the cost planning. Therefore, this reveals that more than one CPE will get connected to the BS.

7.3 Future Work

This thesis focuses on two key components of disaster management systems: wireless hybrid networks and users' application algorithms. An obvious extension of our research would be multiple system integration and the overall system optimization. To achieve this target, the following research challenges should be considered:

- Different heterogeneous QoS mapping to optimize the overall throughput and delay;
- Integration of WiFi + LTE hybrid systems for first responders in disaster or emergency situations;
- Development of numerical metrics for evaluation and comparison of the integration of WiFi + LTE hybrid systems.

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